Searching for Life in the Universe: How, Where and Why?

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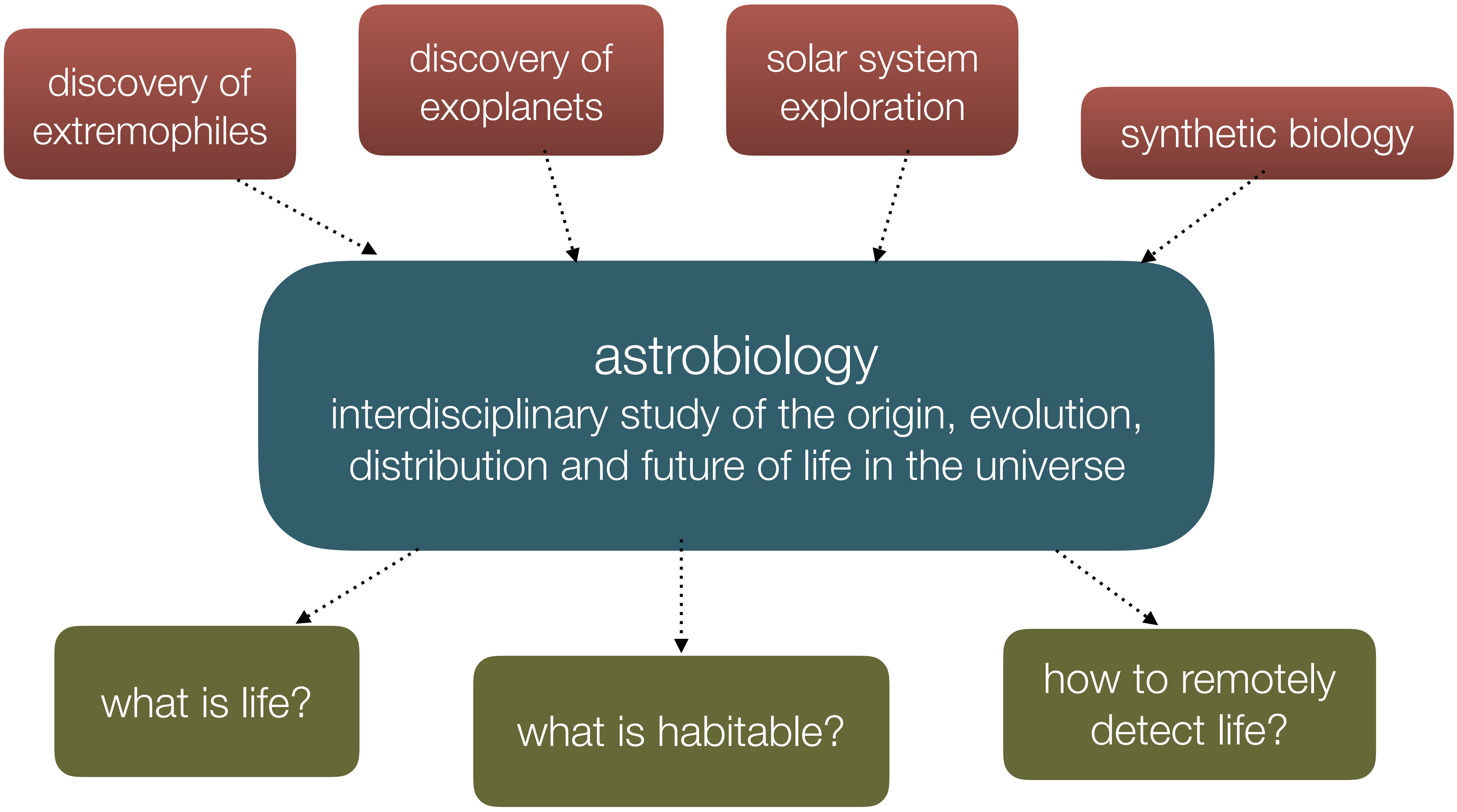
experimental milestones



discovery of extremophiles

discovery of exoplanets

solar system exploration

synthetic biology

astrobiology

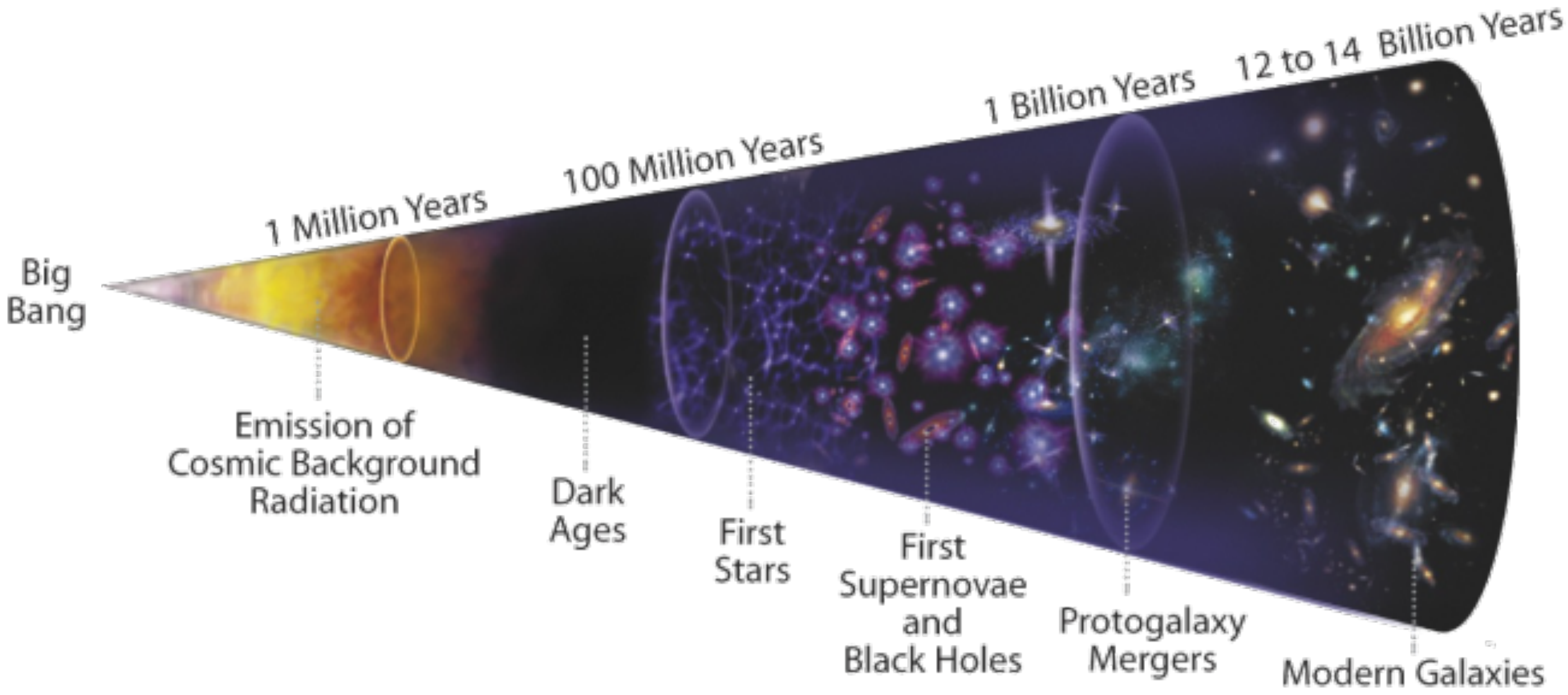
interdisciplinary study of the origin, evolution, distribution and future of life in the universe

what is life?

what is habitable?

how to remotely detect life?

theoretical issues

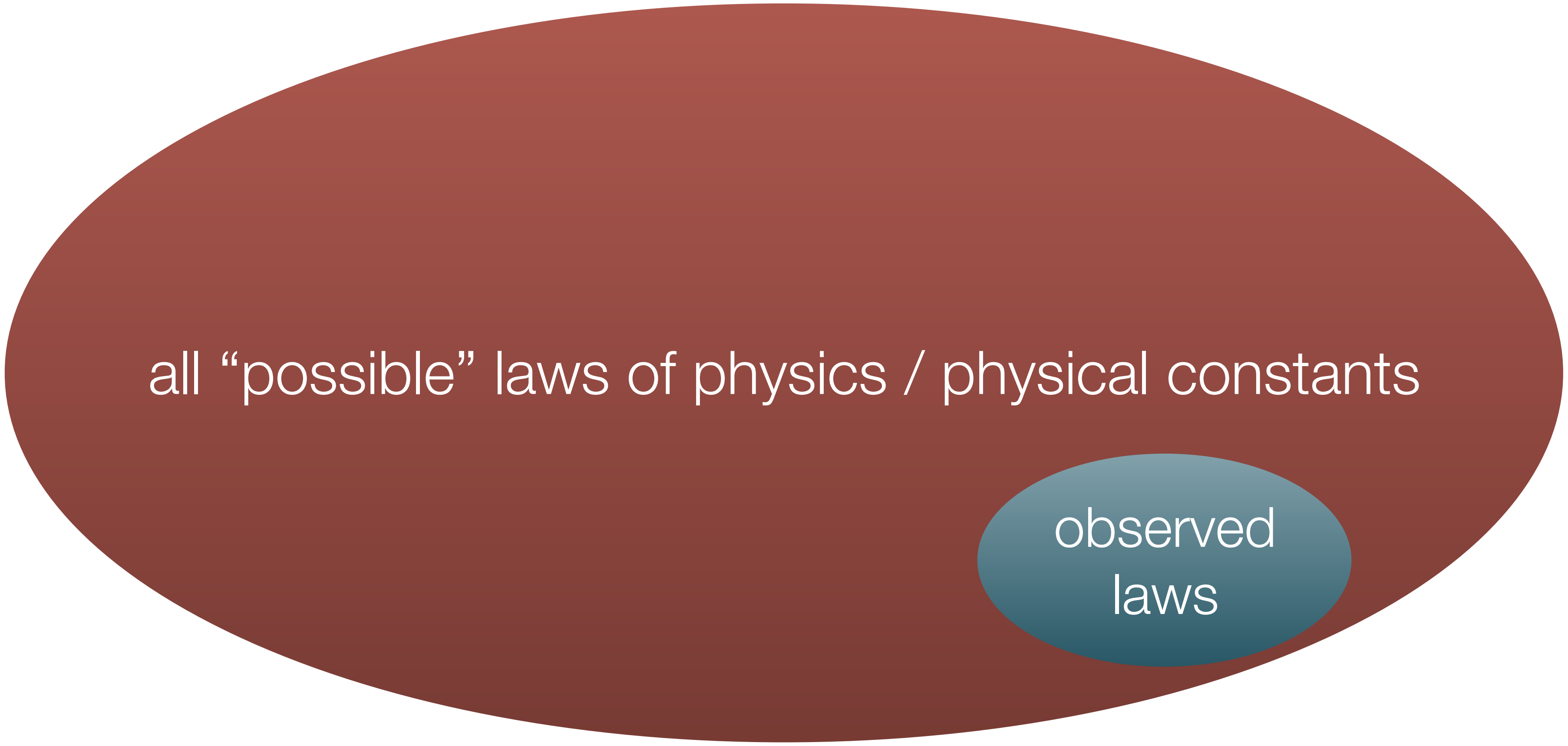


simplicity
smoothness
equilibrium

complexity
clumpiness
disequilibrium

where does life fit in?
how typical is it?

understanding what life is, what are its limits and what is its distribution in the universe might have some impact on cosmology and particle physics



life needs fine-tuning of physical laws

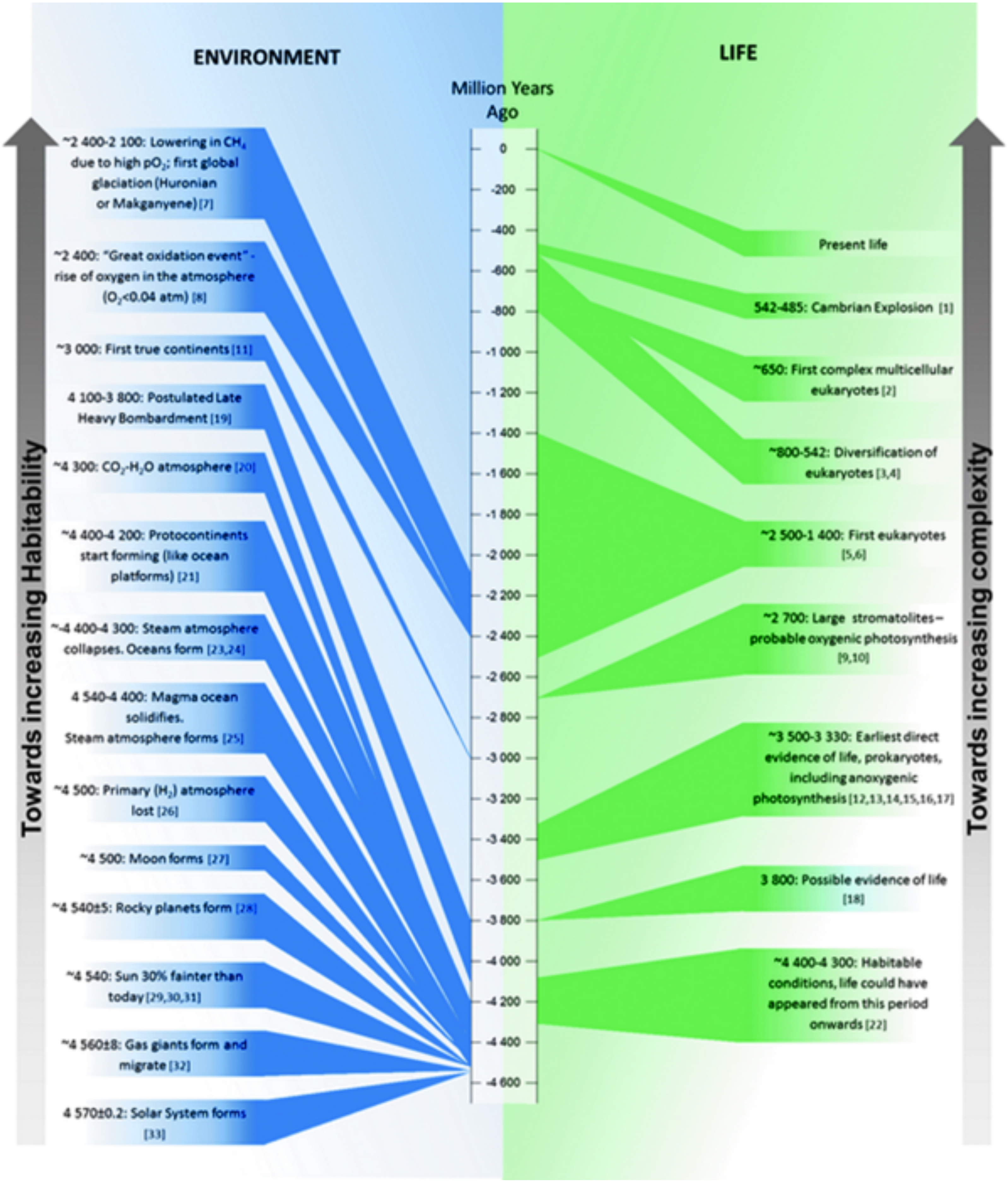
see e.g., Tegmark, Aguirre, Rees & Wilczek 2006; Barnes 2012

observed laws are environmental (multiverse+anthropic selection)

life will appear in almost any physical circumstance

see e.g., Loeb 2013; Harnik, Kribs, and Perez 2006

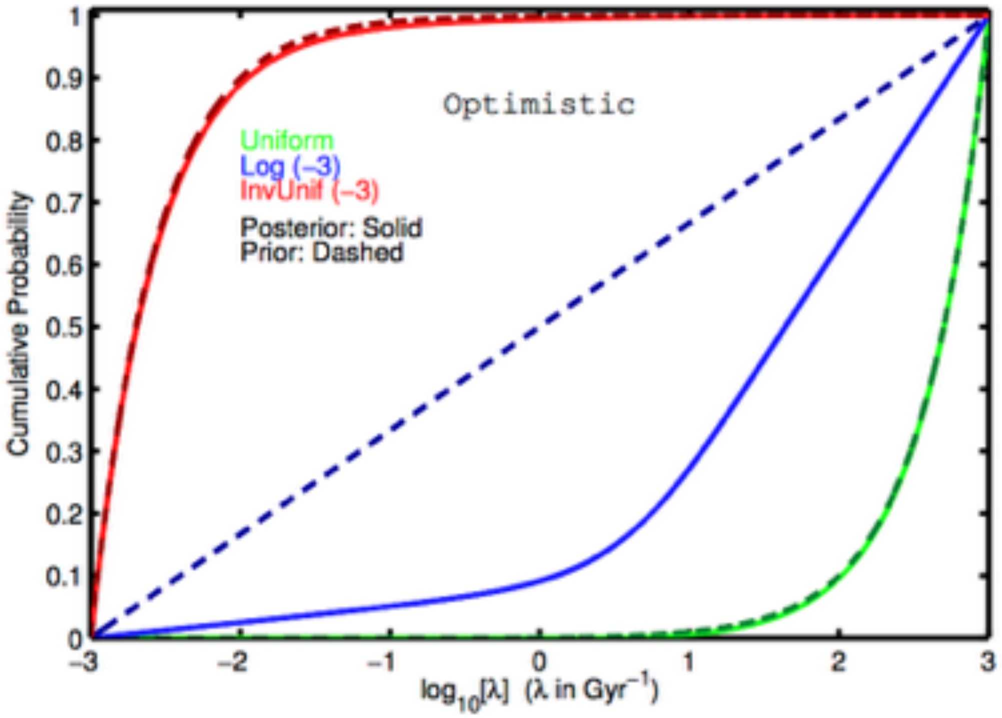
no anthropic explanation



Horneck et al 2016

what can we infer regarding the possible abundance of life in the universe from the early emergence of life on Earth?

almost nothing: for example, Spiegel & Turner (2012) use a Bayesian analysis to show that the posterior probability for abiogenesis almost completely reflects the chosen prior probability; the result, however, changes dramatically when one assumes evidence of even just one independent instance of abiogenesis, both on Earth or beyond (see also Korpela 2011, Brewer 2008)



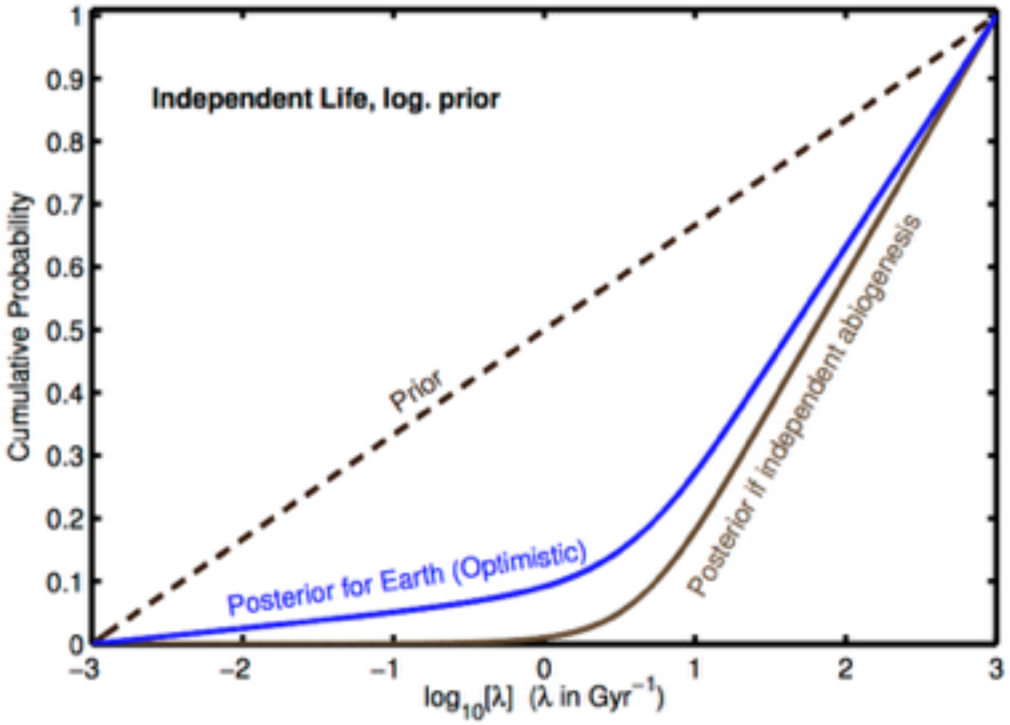
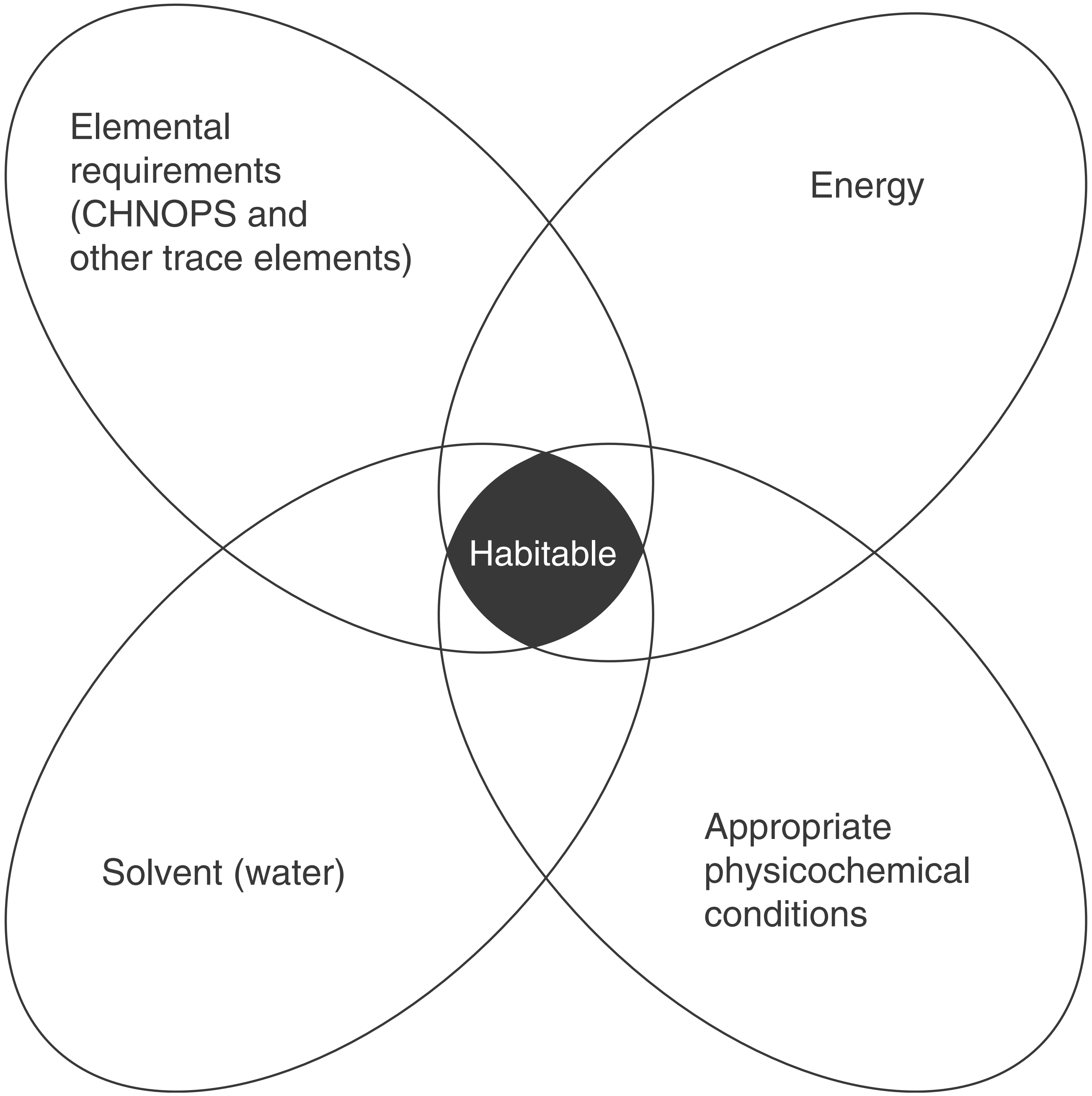


Fig. 2. CDF of λ for abiogenesis with independent lineage, for logarithmic prior. $\lambda_{\rm min} = 10^{-3}{\rm Gyr}^{-1}$, $\lambda_{\rm max} = 10^{3}{\rm Gyr}^{-1}$. A discovery that life arose independently on Mars and Earth or on an exoplanet and Earth – or that it arose a second, independent, time on Earth – would significantly reduce the posterior probability of low λ.

where to look for?



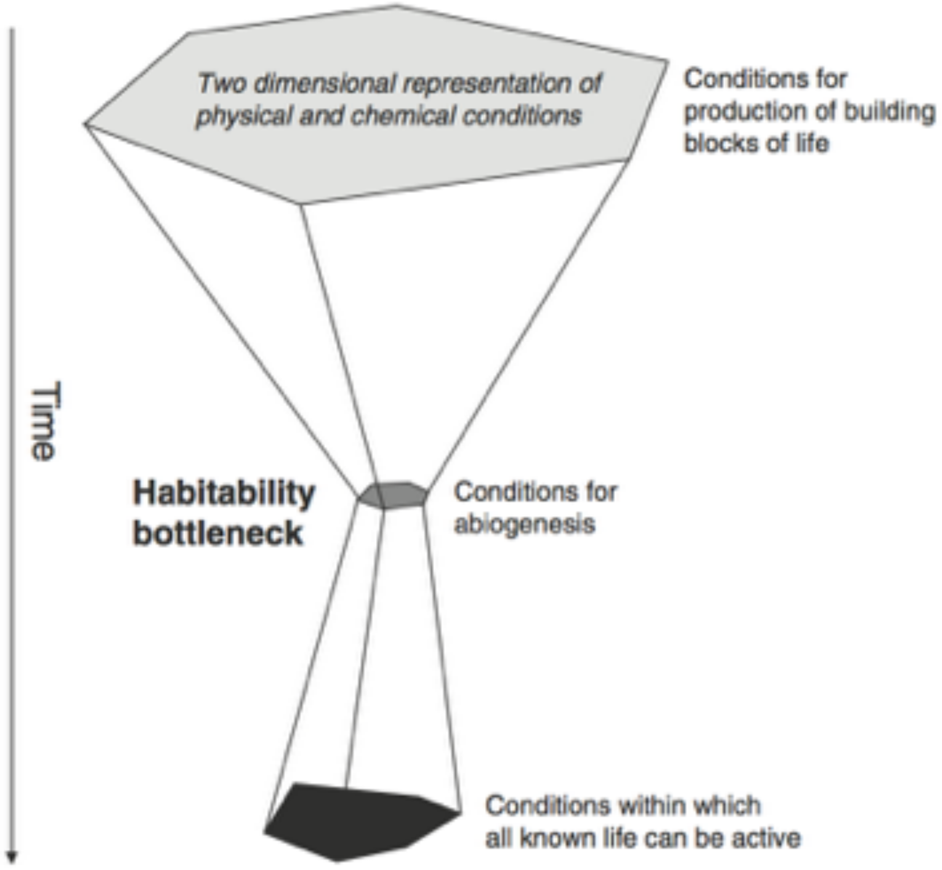
Elemental requirements (CHNOPS and other trace elements)

Energy

Habitable

Solvent (water)

Appropriate physicochemical conditions



Cockell et al. 2016

Boundaries continue to expand...

acidophiles

Xerophiles

endoliths

psychrophiles

Temperature limits for life

1960 = 65°C

1980 = 101°C

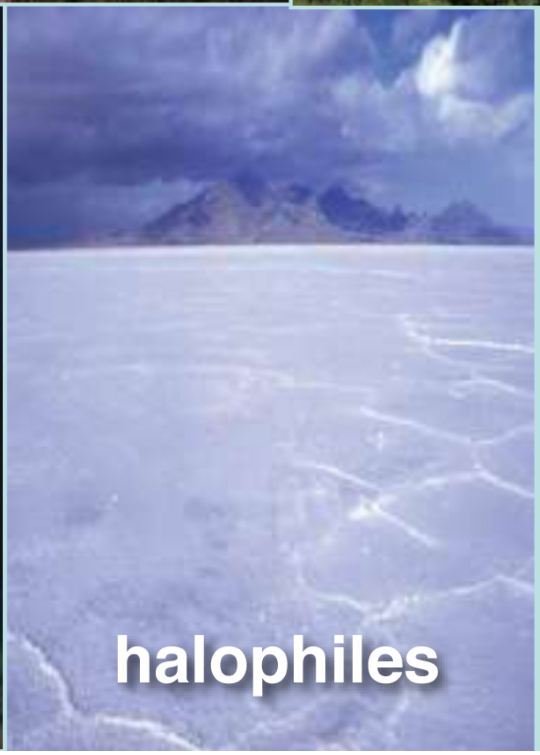
2004 = 118°C

thermophiles

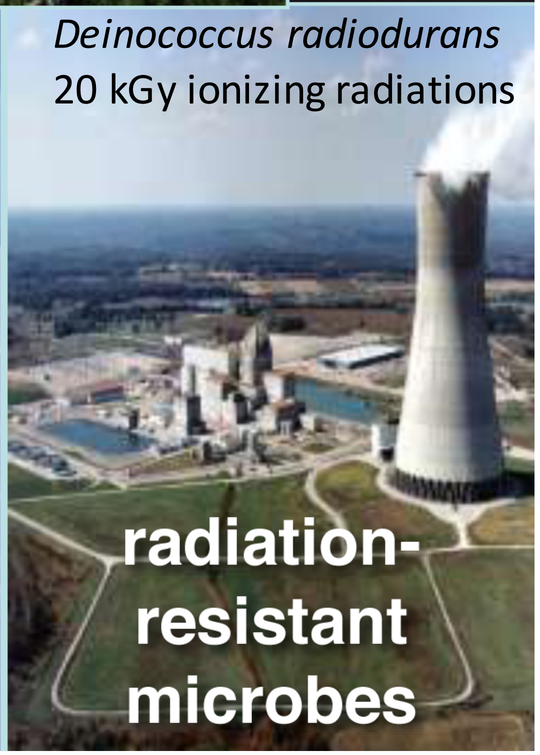
spacephiles

alkaliphiles

barophiles



halophiles

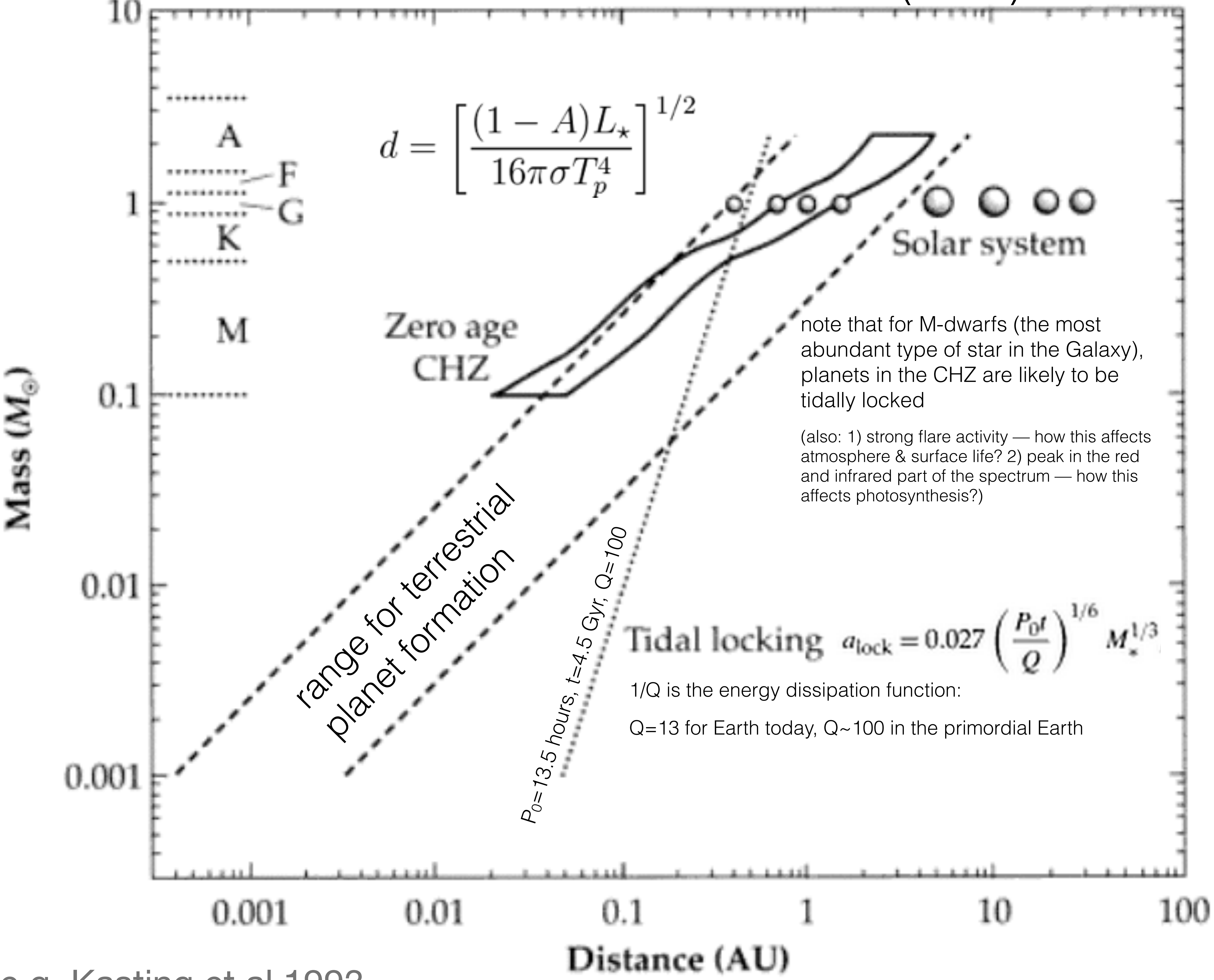


Deinococcus radiodurans

20 kGy ionizing radiations

radiation-resistant microbes

circumstellar habitable zone (CHZ)



$$d = \left[\frac{(1-A)L_\star}{16\pi\sigma T_p^4}\right]^{1/2}$$

Tidal locking $a_{\rm lock} = 0.027\left(\frac{P_0 t}{Q}\right)^{1/6} M_\star^{1/3}$

range for terrestrial planet formation

P_0=13.5 hours, t=4.5 Gyr, Q=100

note that for M-dwarfs (the most abundant type of star in the Galaxy), planets in the CHZ are likely to be tidally locked

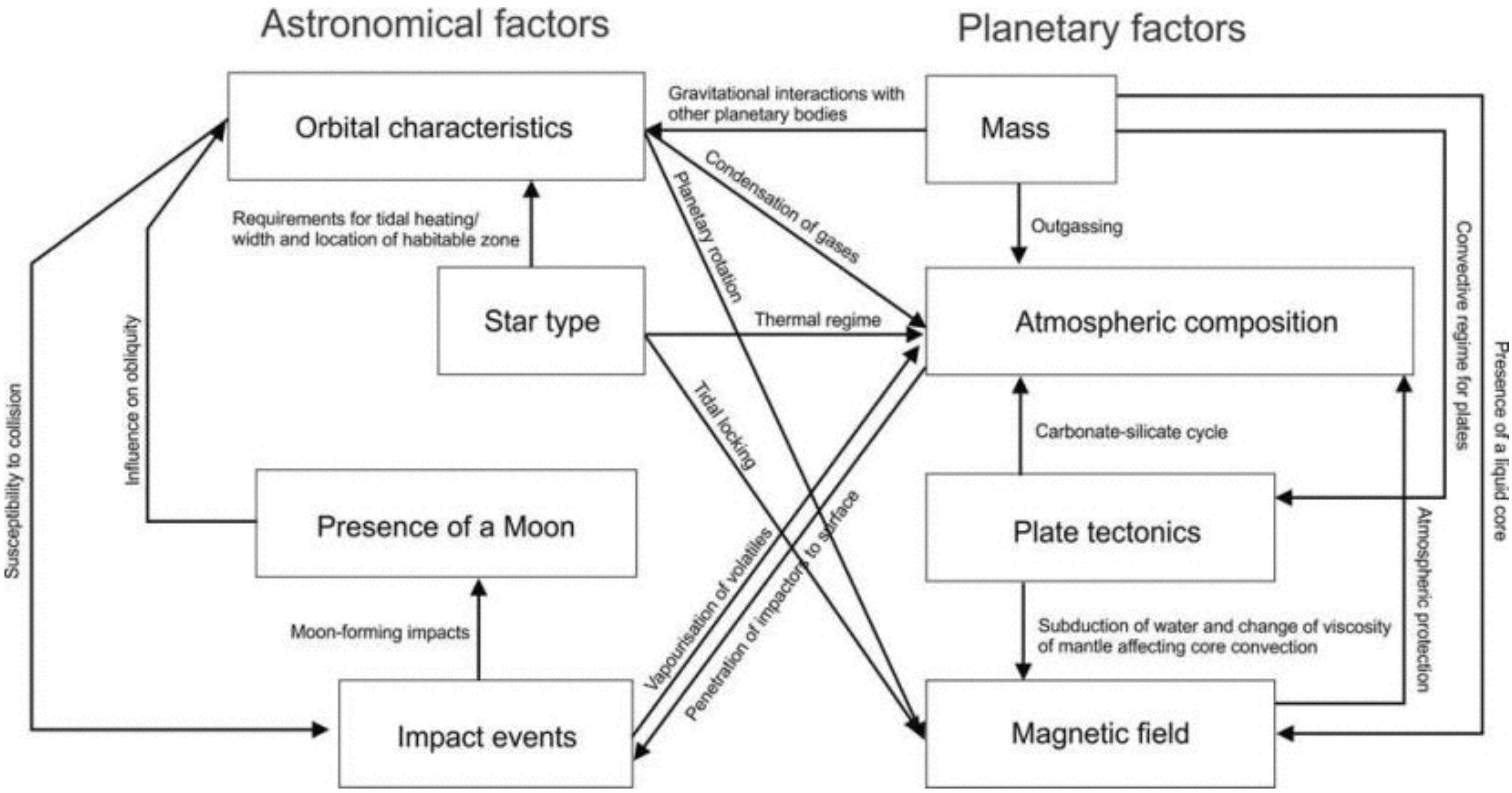
(also: 1) strong flare activity — how this affects atmosphere & surface life? 2) peak in the red and infrared part of the spectrum — how this affects photosynthesis?)

1/Q is the energy dissipation function:

Q=13 for Earth today, Q~100 in the primordial Earth

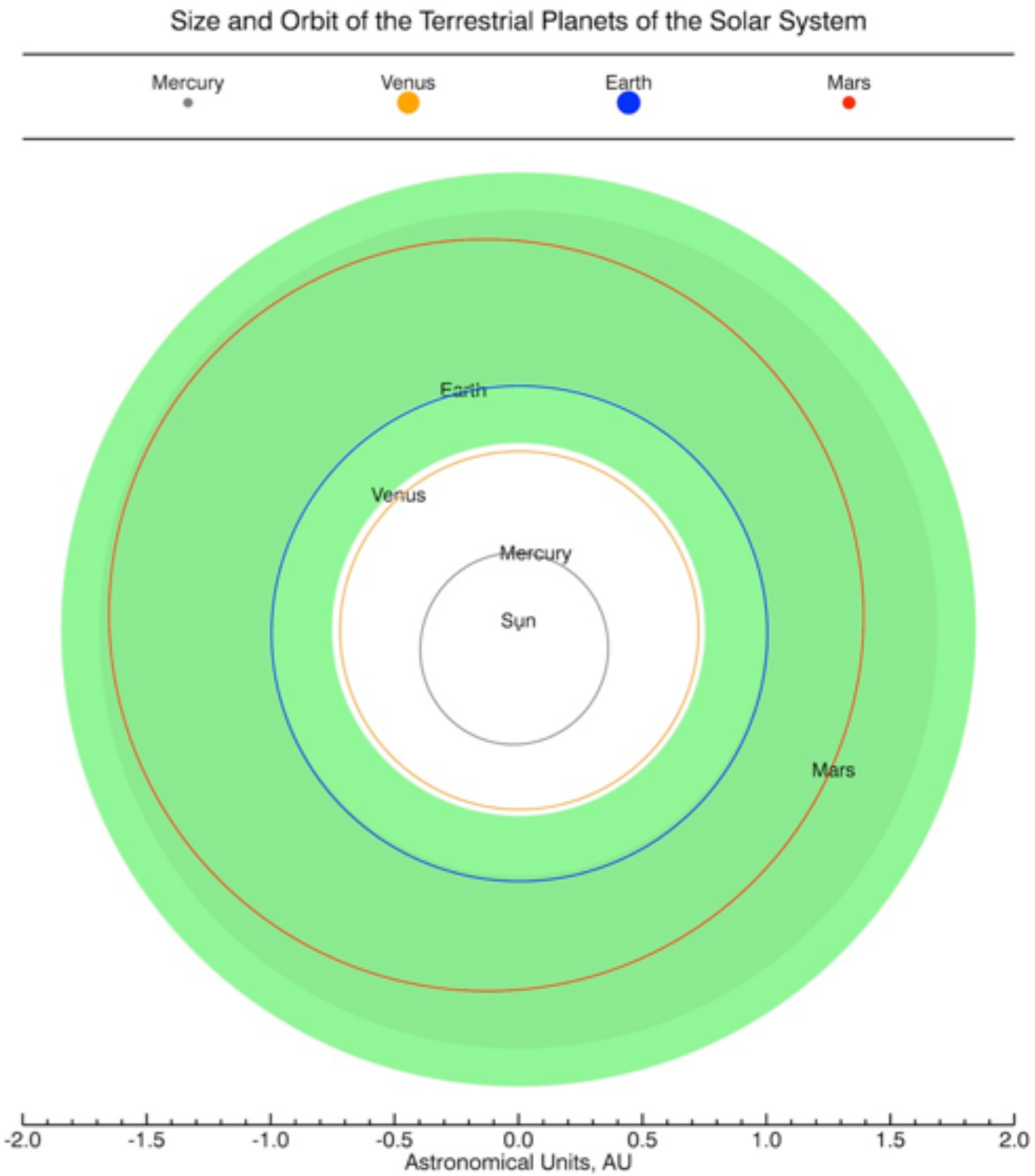
see e.g. Kasting et al 1993

but real life is complicated…



Cockell et al. 2016

lessons from the solar system



phl.upr.edu, Apr 2013

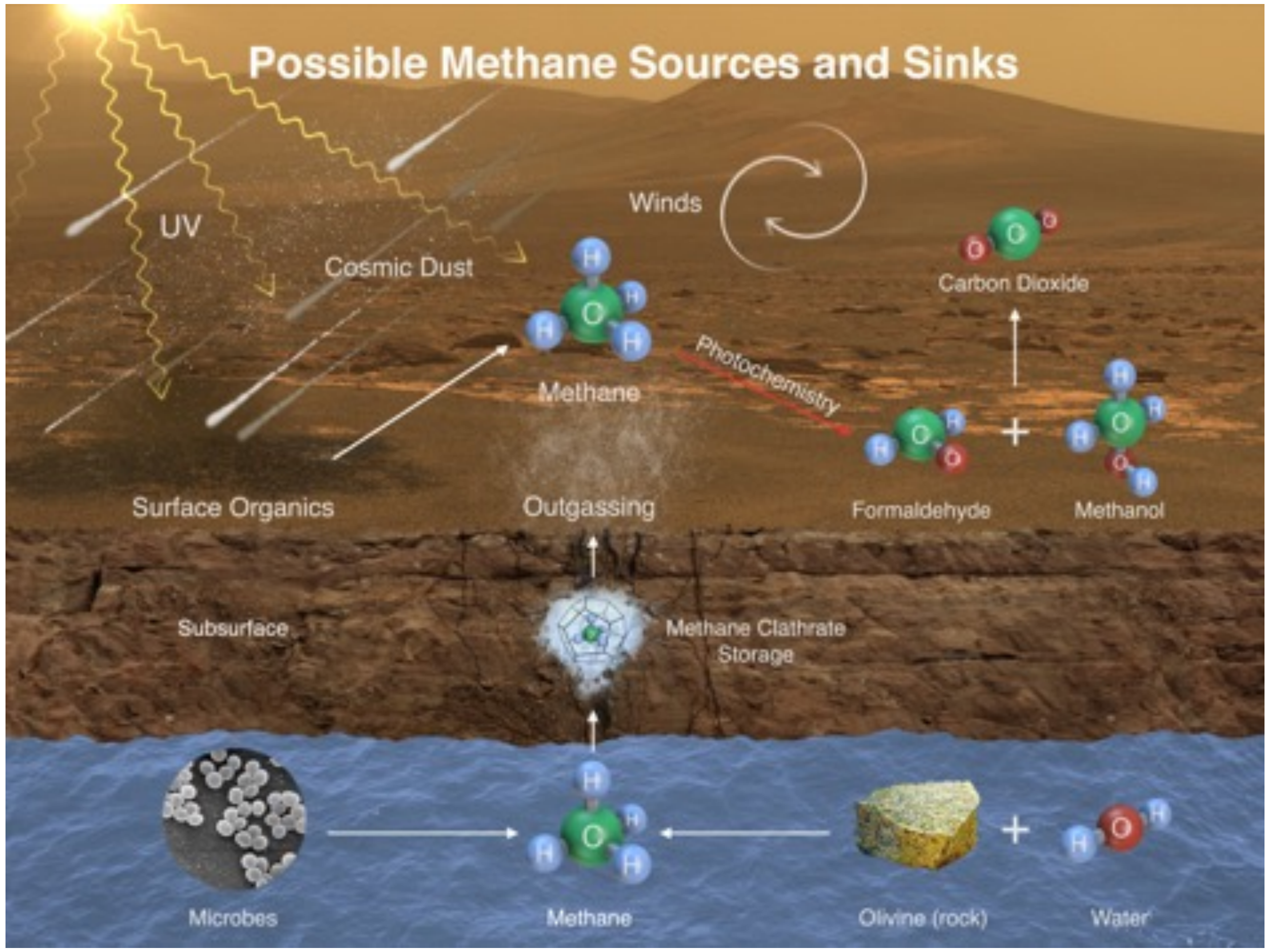
Venus: too thick CO_2 atmosphere (90 bar), runaway greenhouse, lack of tectonic, T~500°C

Mars: too thin CO_2 atmosphere (0.006 bar, close to water triple point), no greenhouse, no magnetic field, lack of tectonic, volcanism, T~-50°C

they both had milder conditions in the past, with strong evidence for stable liquid water on Mars

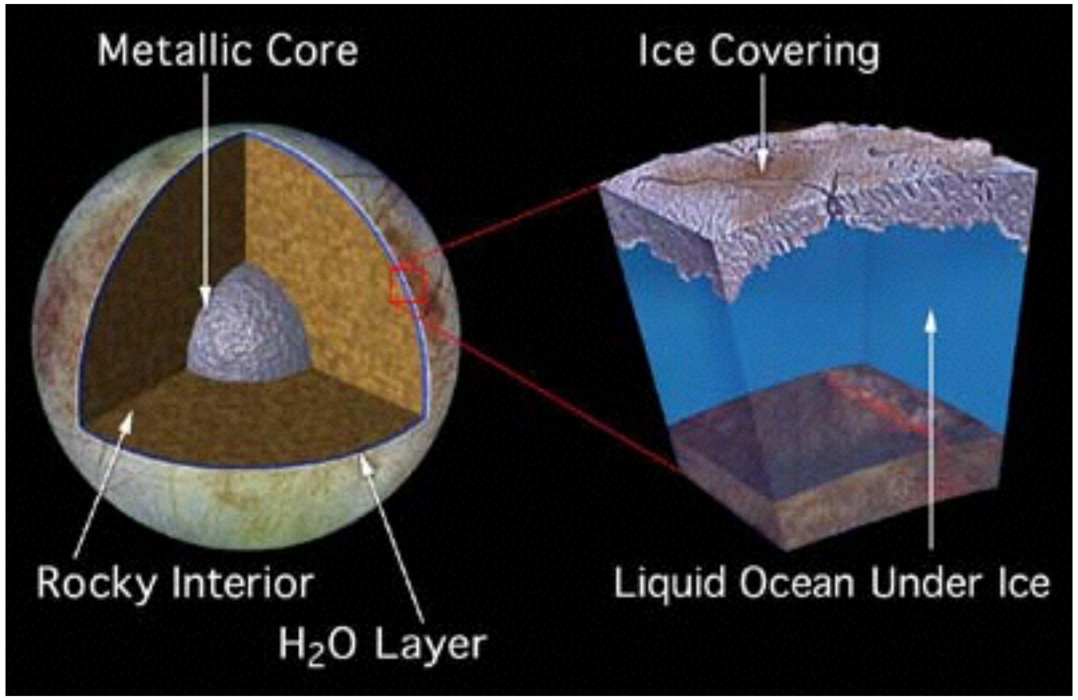
habitability of Mars

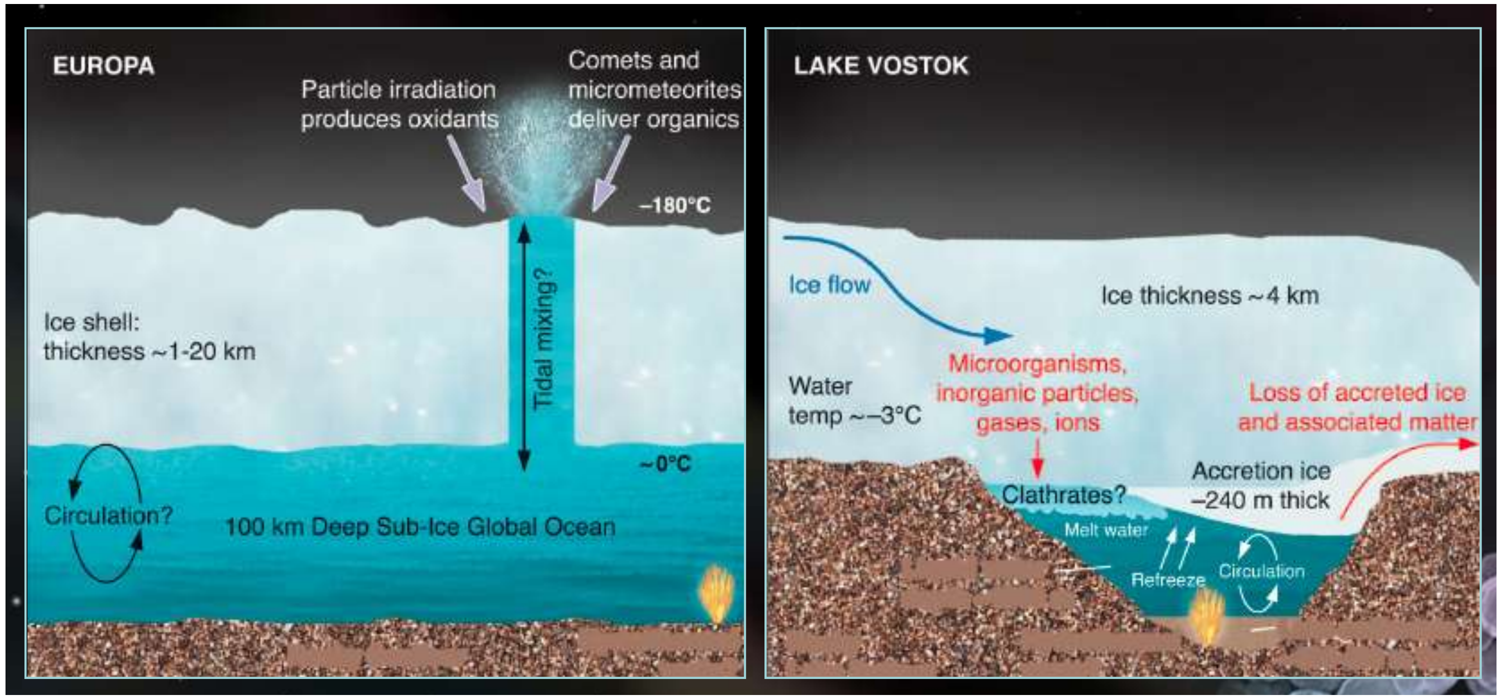
- Today, the dry dusty soil at the surface of Mars is unlikely to be habitable because of high levels of high-frequency UV radiation and of oxidation due to peroxide and perchlorate
- No sign of present life was conclusively found on Mars by probes explicitly designed with this science goal (Viking mission, 1976)
- Life could have originated on Mars in the past and gone extinct, or it might still be present in isolated niches (e.g. below the surface or beneath rocks)
- ExoMars will look for present and past signs of life



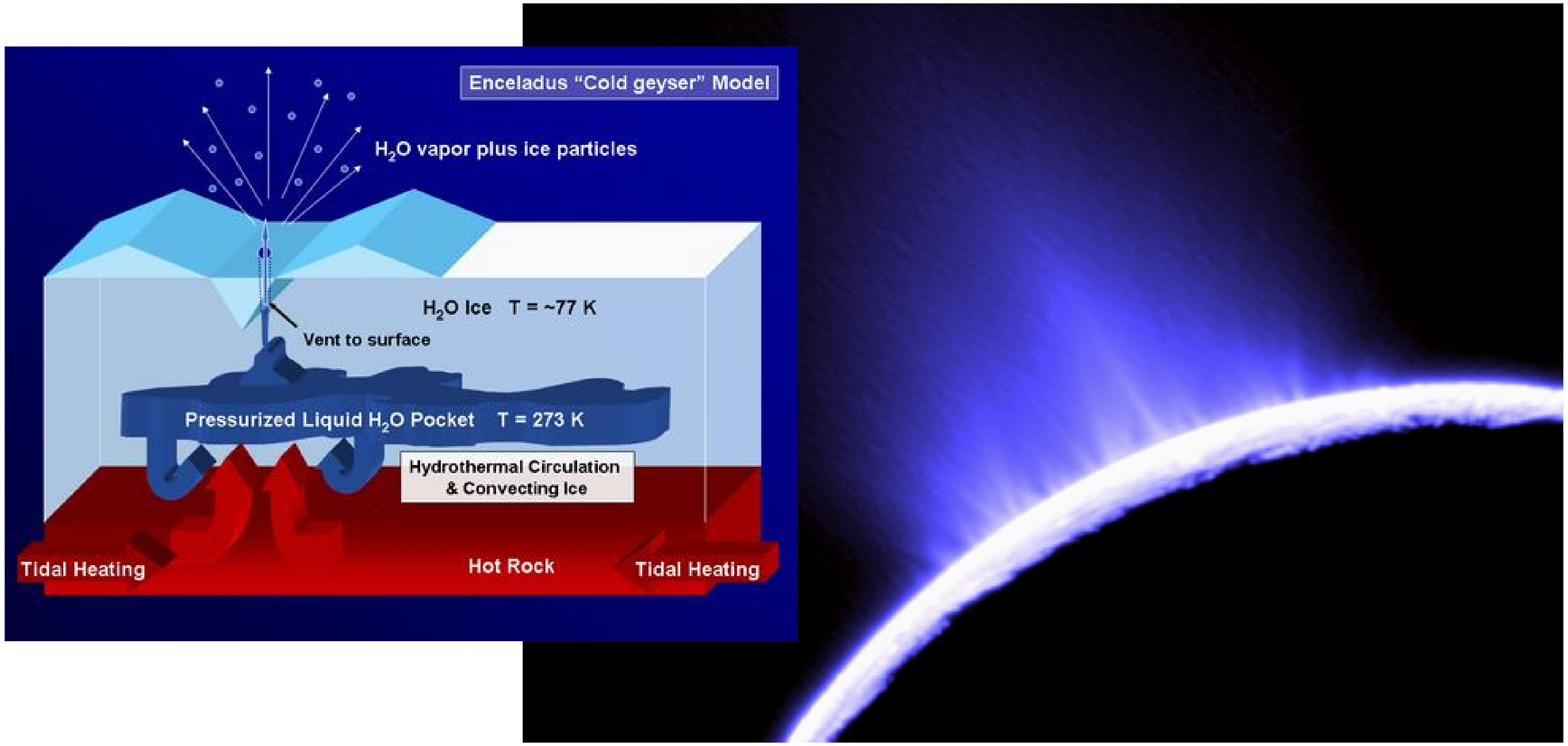
habitability outside the CHZ

example: icy moons of the Solar System (Europa, Enceladus)



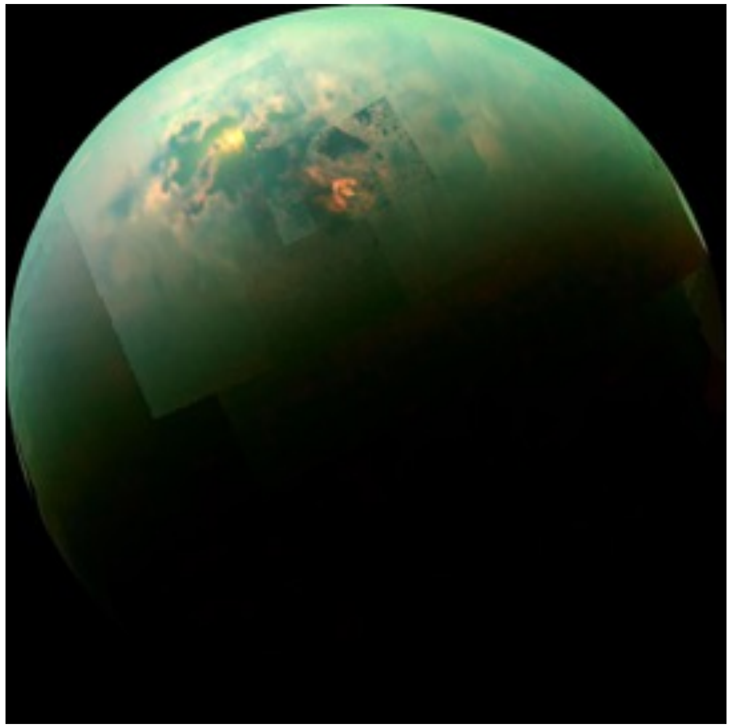


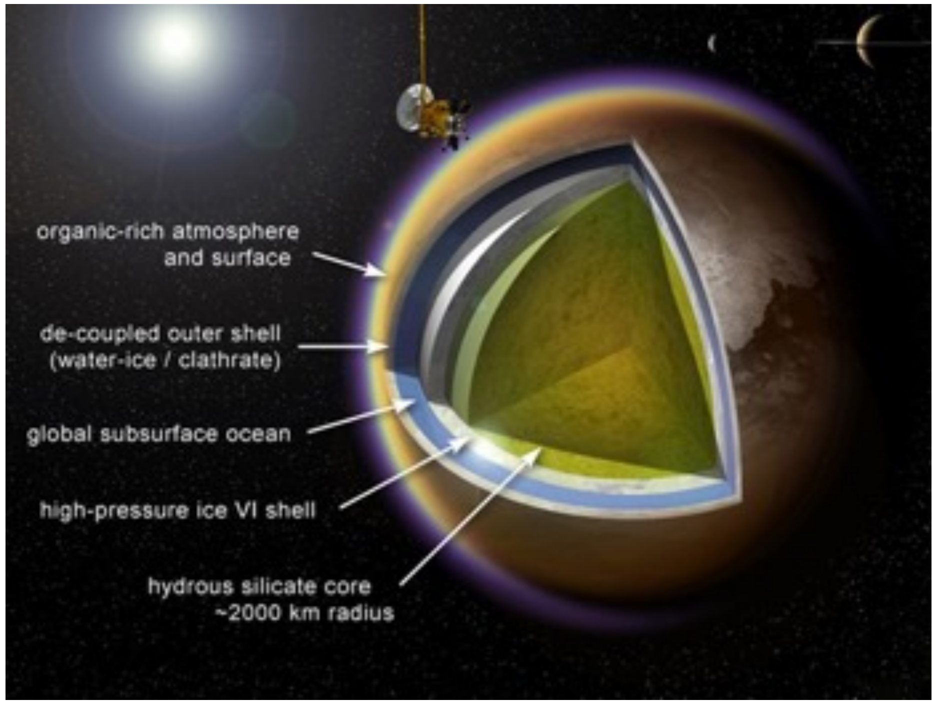
more to come from present (Cassini) and future (i.e. JUICE) space missions

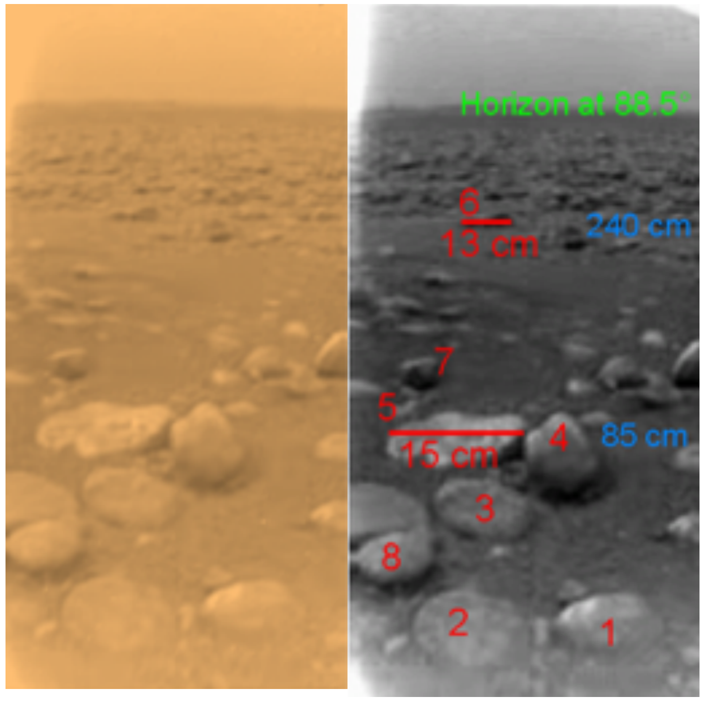


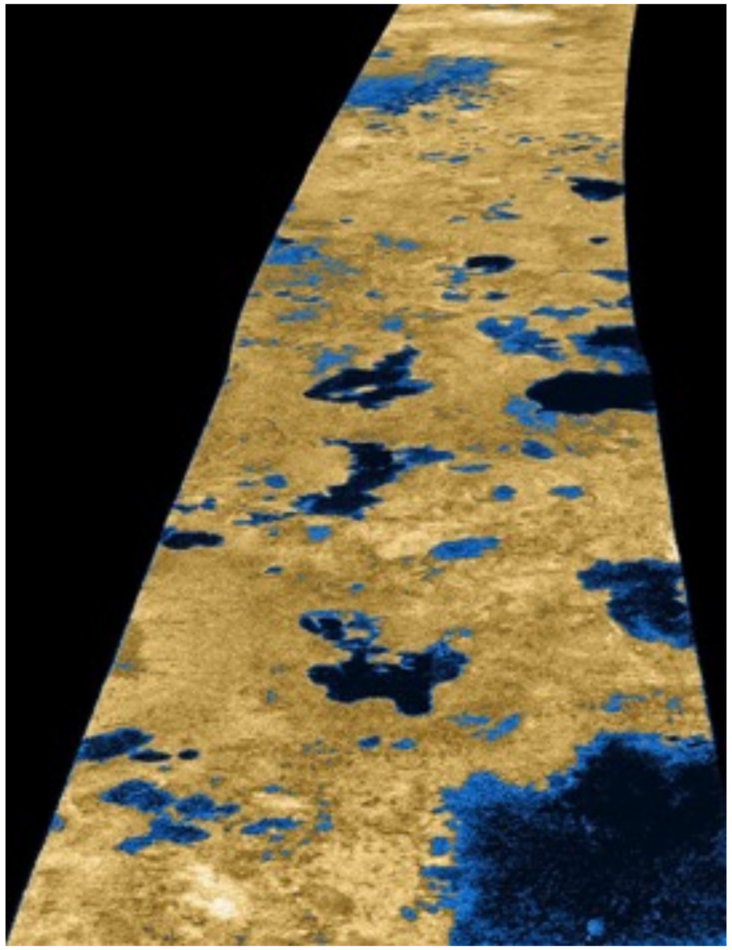
habitability outside the CHZ

example: Titan



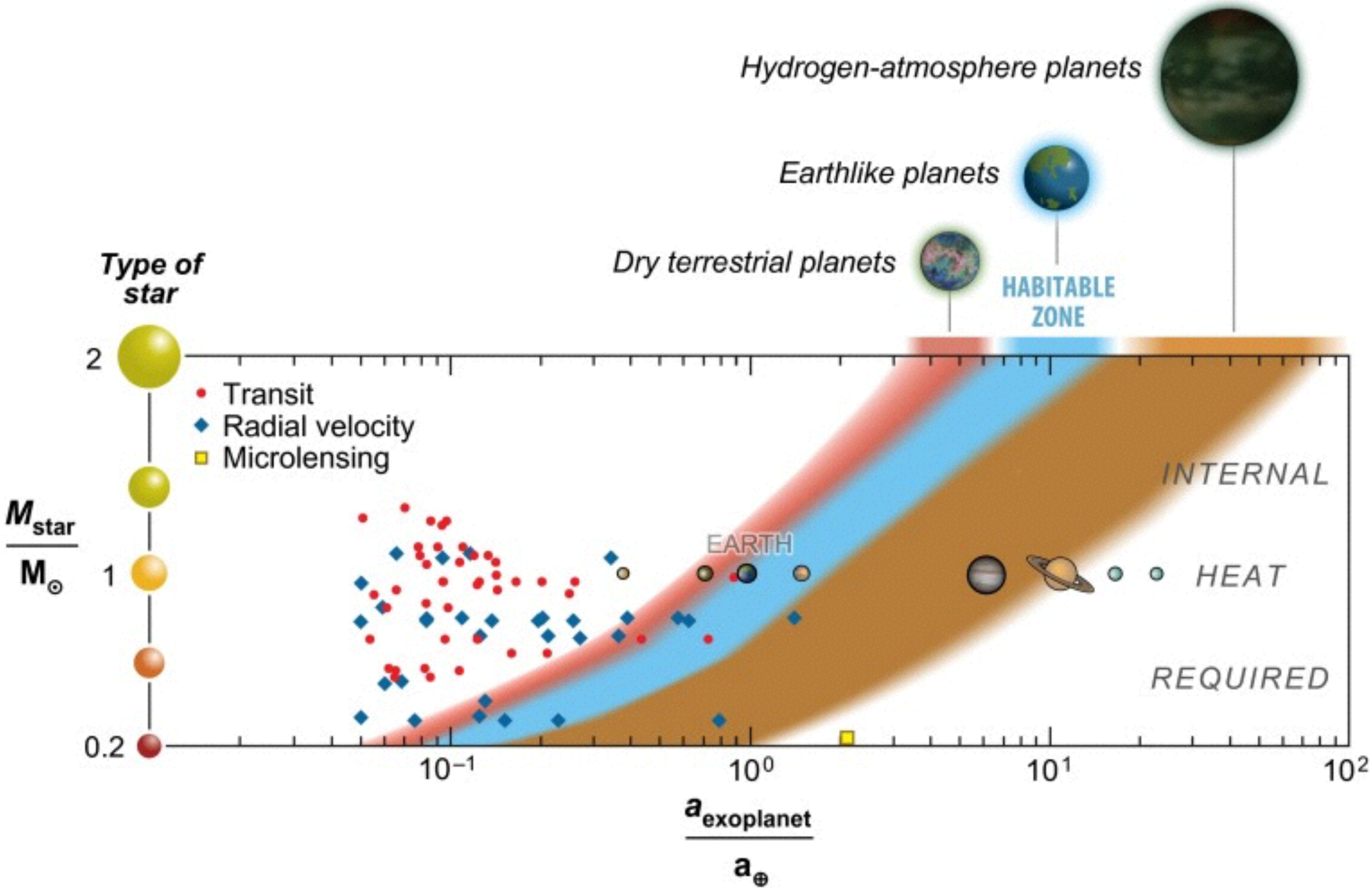






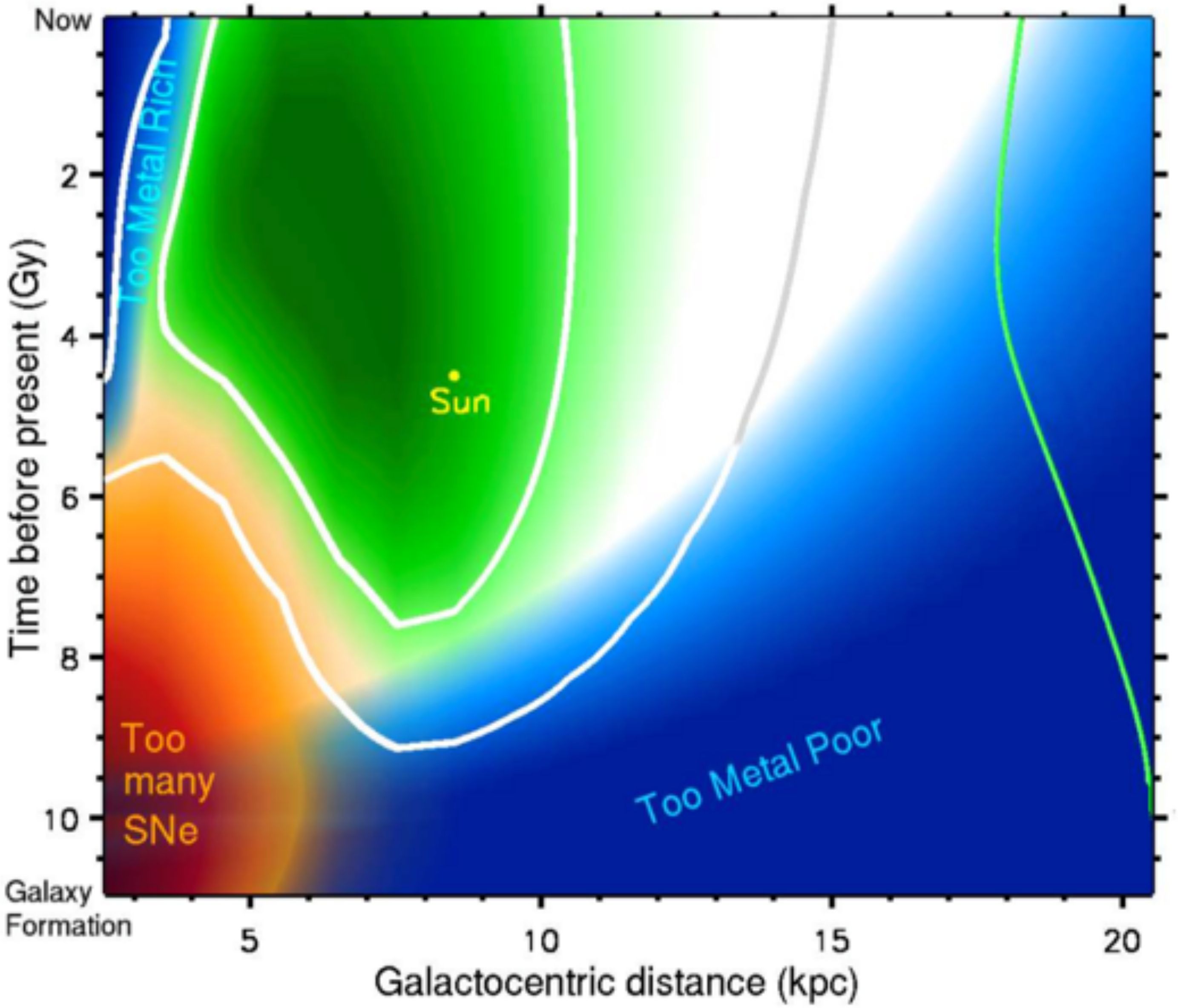
- rocky active surface, covered with ethane-methane lakes, possibly criovolcanism and a methane cycle
- thick atmosphere, mostly gaseous nitrogen
- internal structure models include the possibility of a subsurface water ocean
- photochemical reactions allow for production of rich organic compounds, including HCN, shown to be a precursor of aminoacids in Miller-Urey experiments
- interesting laboratory for complex organic chemistry, including reactions which might have taken place on early Earth
- life is unlikely at temperatures as low as those on Titan surface and in liquid hydrocarbons, but there may be better conditions under the surface
- might be very similar to the most common kind of rocky planets in the galaxy, those orbiting M2 (red dwarf) stars
- any life form on Titan would be radically different than on Earth, opening exciting possibility for a completely independent origin

extended habitable zone

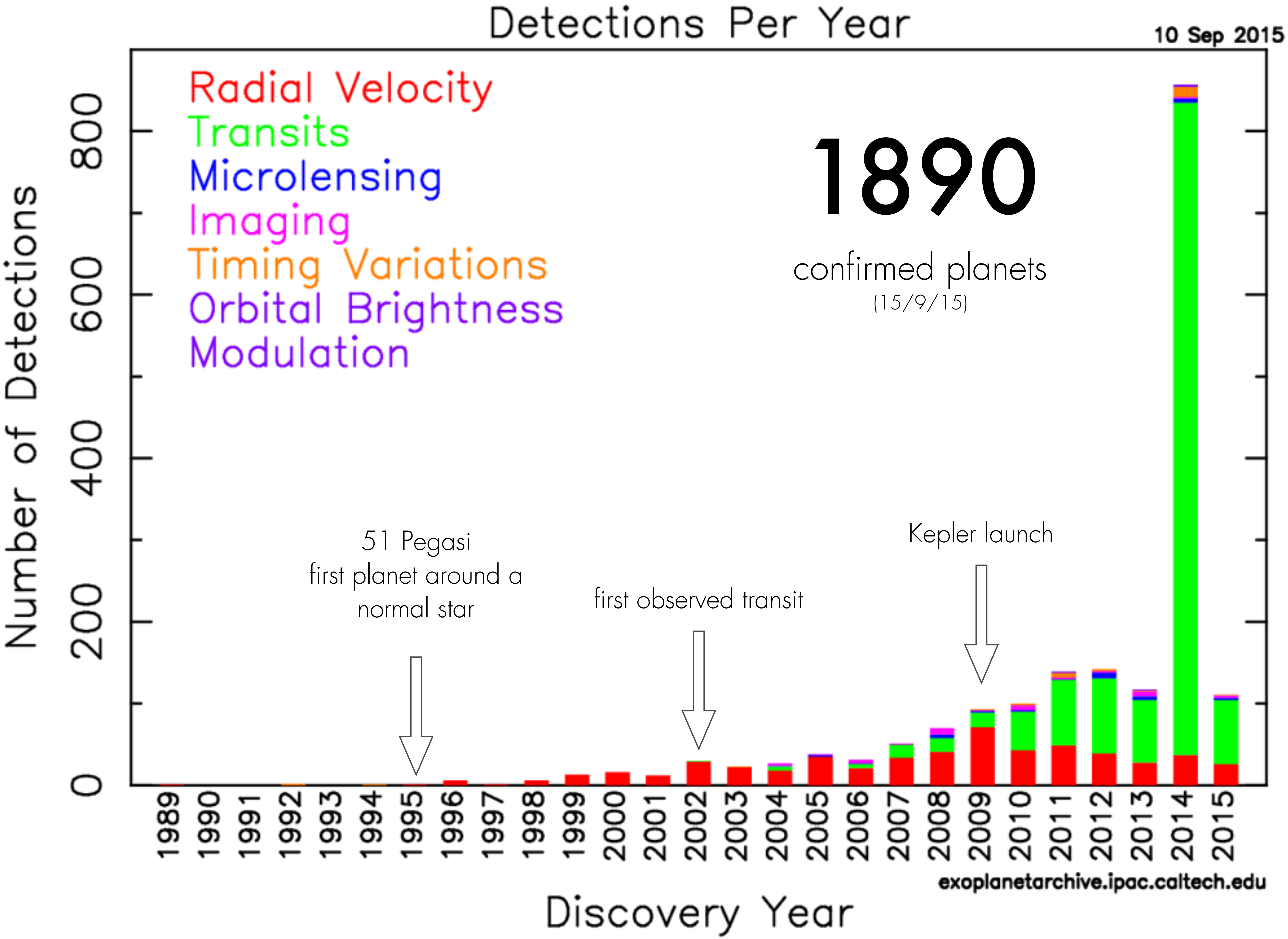


Seager 2014

galactic habitable zone



Lineweaver et al. 2004



1890

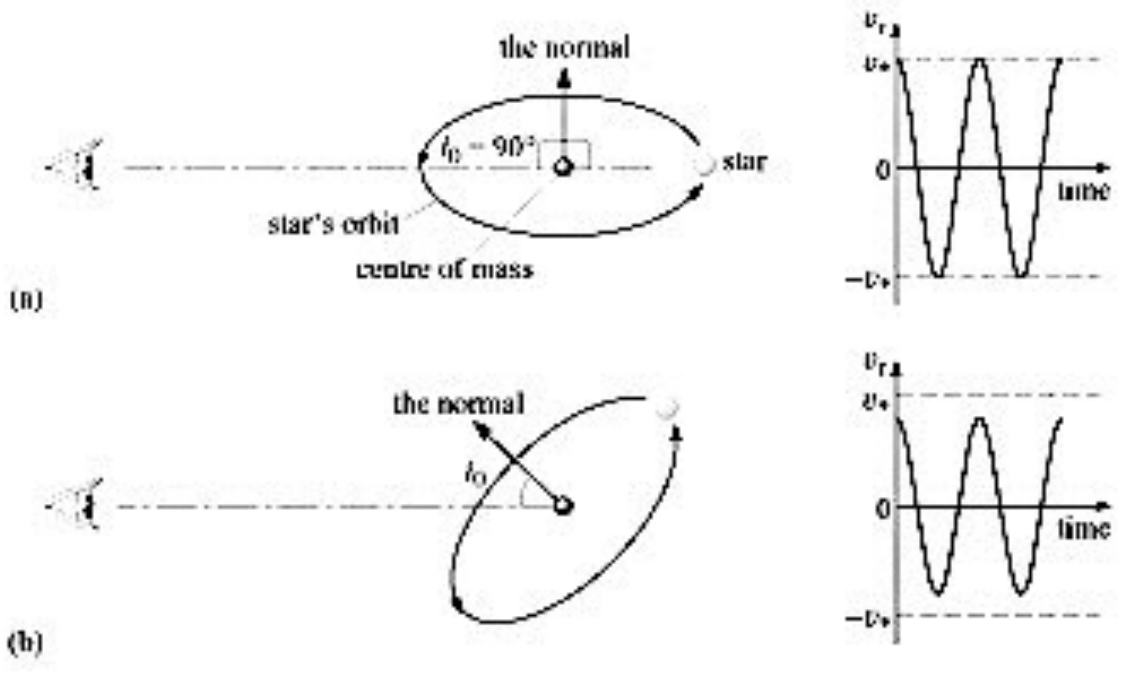
confirmed planets
(15/9/15)

51 Pegasi
first planet around a
normal star

first observed transit

Kepler launch

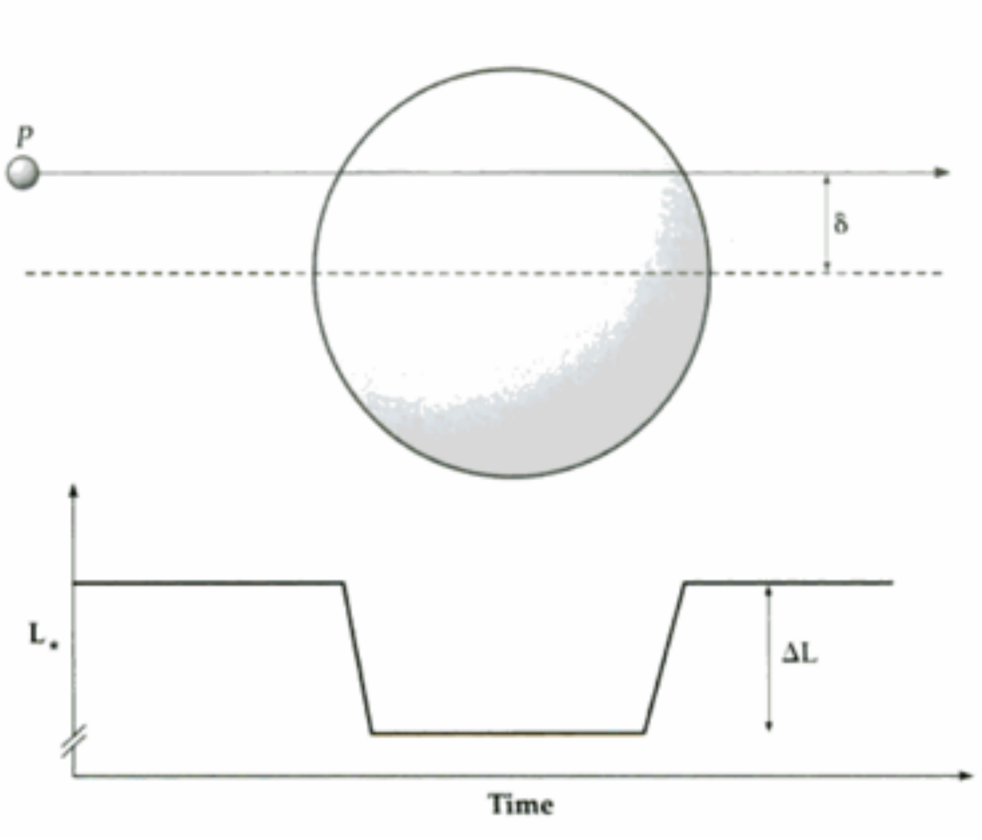
radial velocity



$$v_r^{\max} = 28.4 \left(\frac{P}{1\mathrm{yr}}\right)^{-1/3} \left(\frac{M_p \sin i}{M_J}\right) \left(\frac{M_\star}{M_\odot}\right)^{-2/3} \ (\mathrm{m/s})$$

- current sensitivity ~1 m/s
- signal from earth-like exoplanets ~10 cm/s (within reach of next-generation ultra-stable spectrometers)
- measurement of mass (lower limit) and period
- 549 confirmed planets until now

transit



$$\frac{\Delta L}{L_*} \simeq \left(\frac{R_p}{R_*}\right)^2 \qquad \tau = \frac{P}{\pi}\left(\frac{R_* \cos\delta + R_p}{a}\right)$$

- signal from earth-like exoplanets $\sim 10^{-4}$ (within reach of current space observations)
- low success rate due to geometric alignment probability
- measurement of radius and period
- atmosphere characterization
- 1233 confirmed planets until now

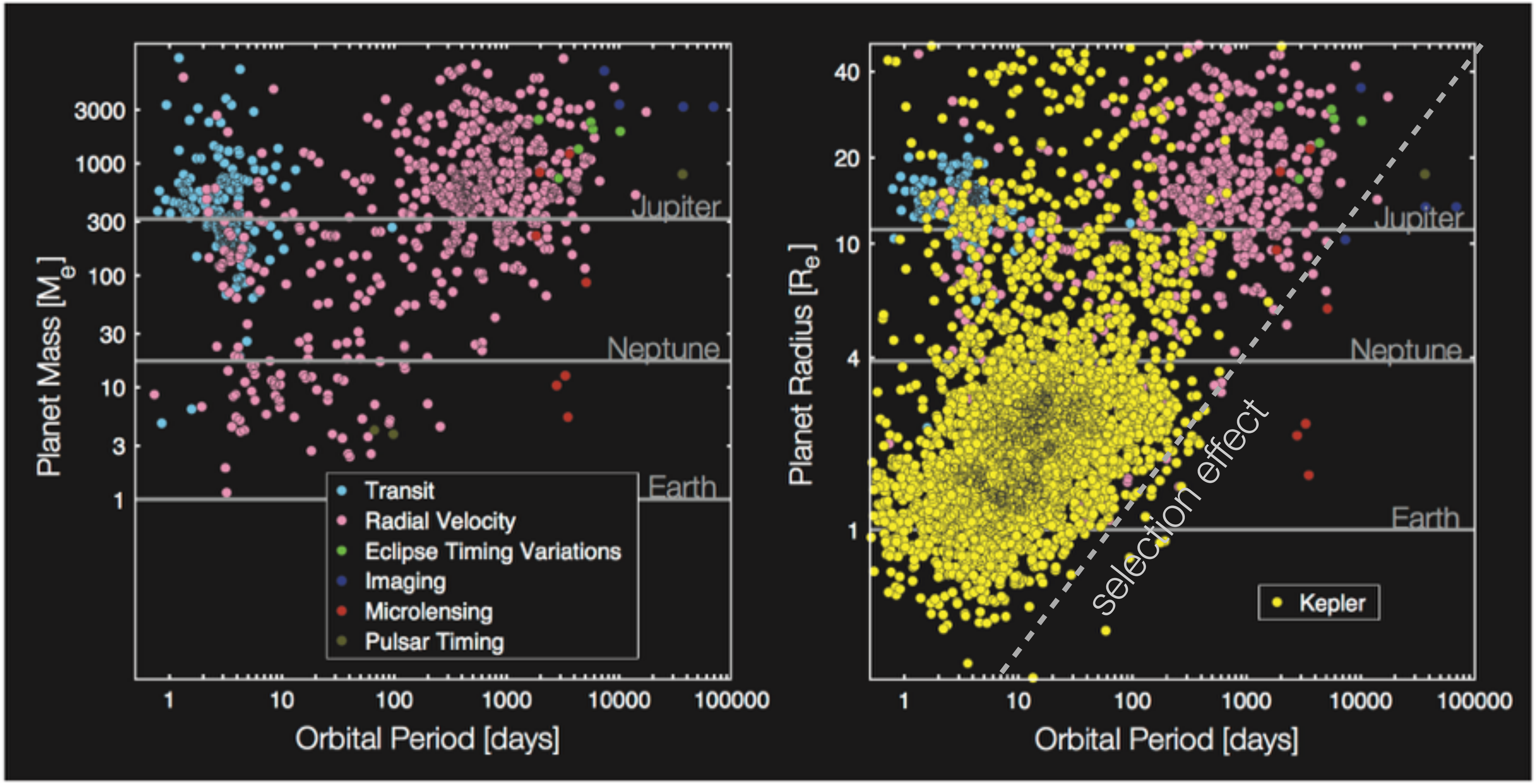
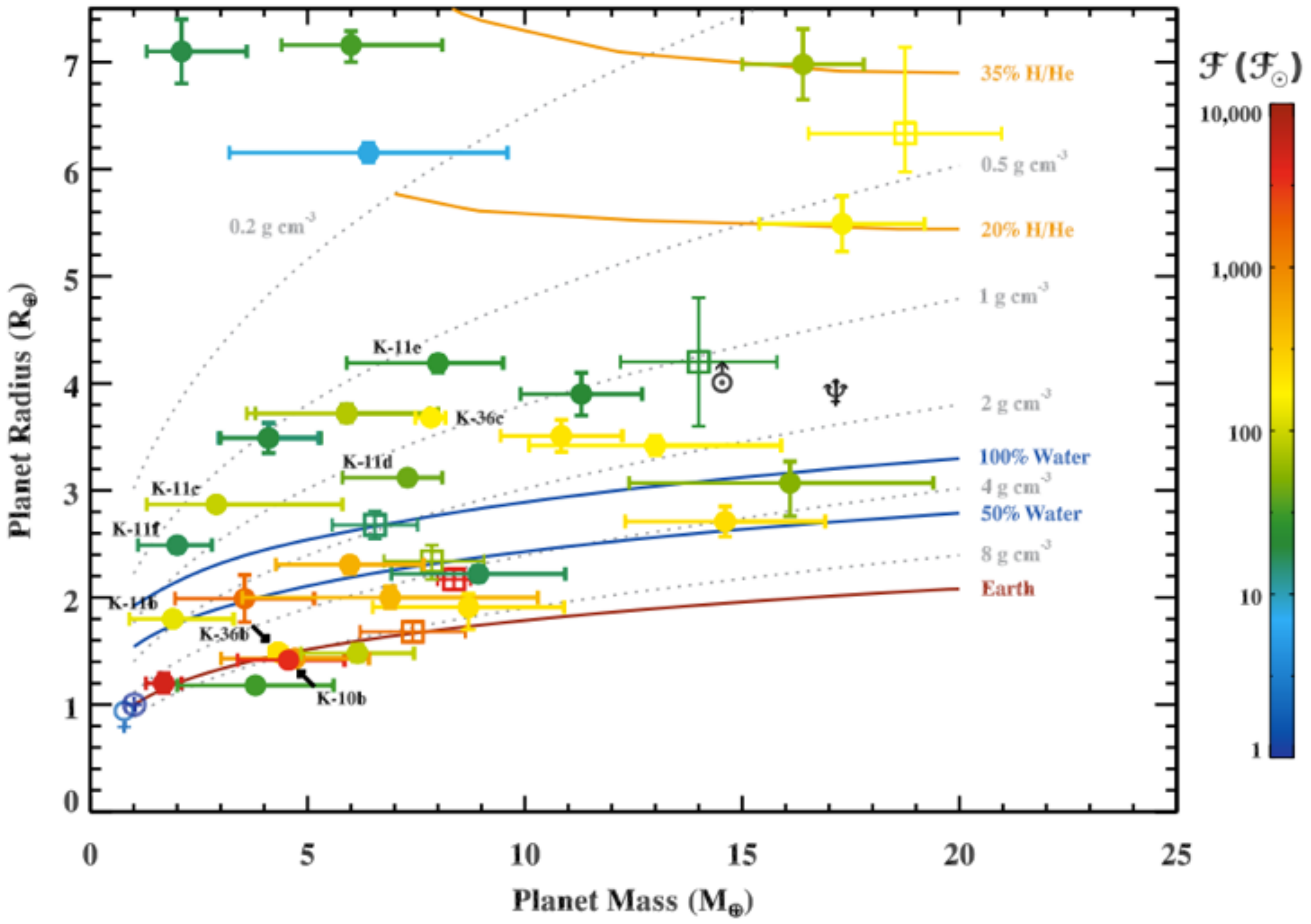


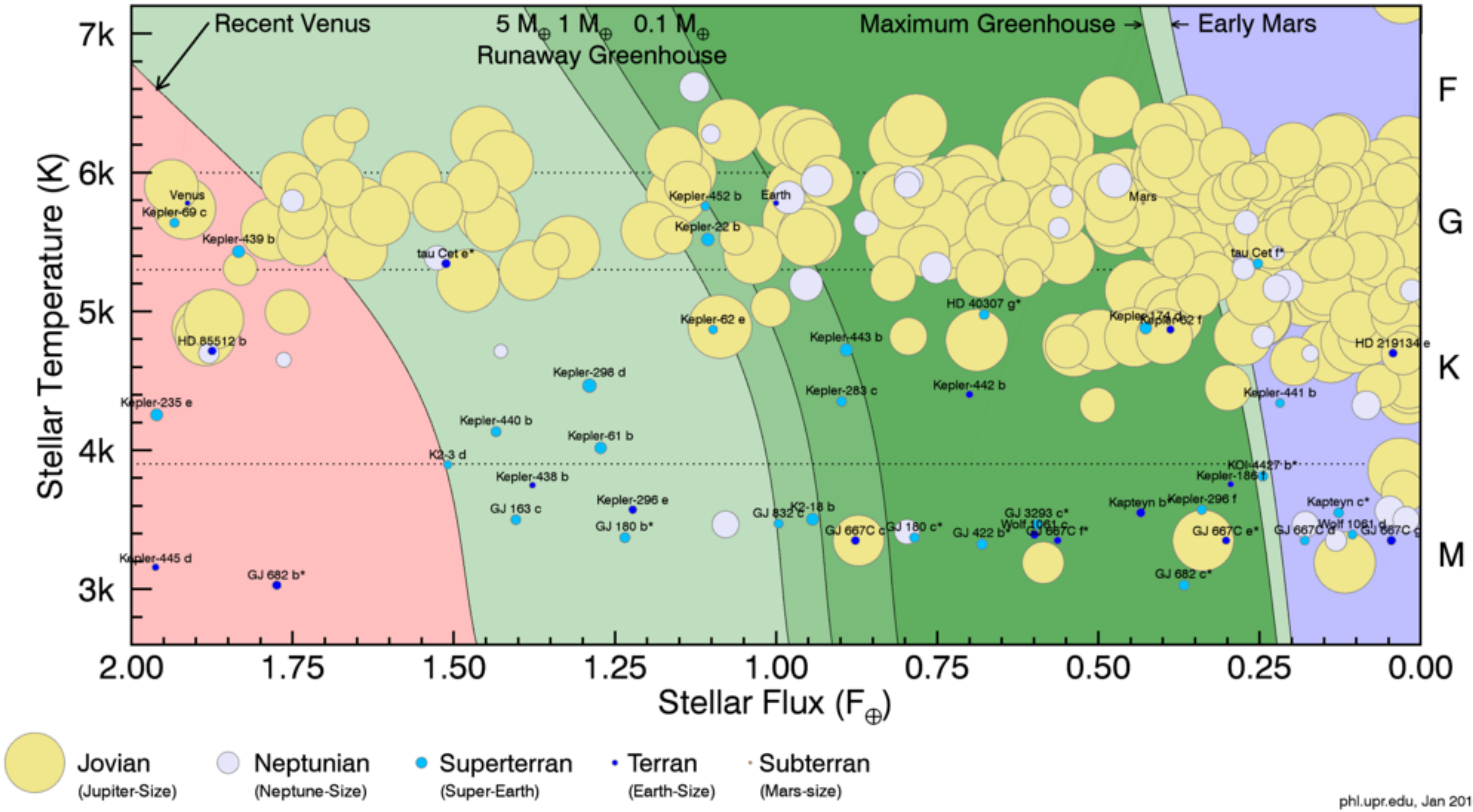
Fig. 1. Non-Kepler exoplanet discoveries (left) are plotted as mass versus orbital period, colored according to the detection technique. A simplified mass-radius relation is used to transform planetary mass to radius (right), and the > 3500 Kepler discoveries (yellow) are added for comparison. 86% of the non-Kepler discoveries are larger than Neptune while the inverse is true of the Kepler discoveries: 85% are smaller than Neptune.

Batalha 2014

radius vs mass and estimated composition for Kepler exoplanets



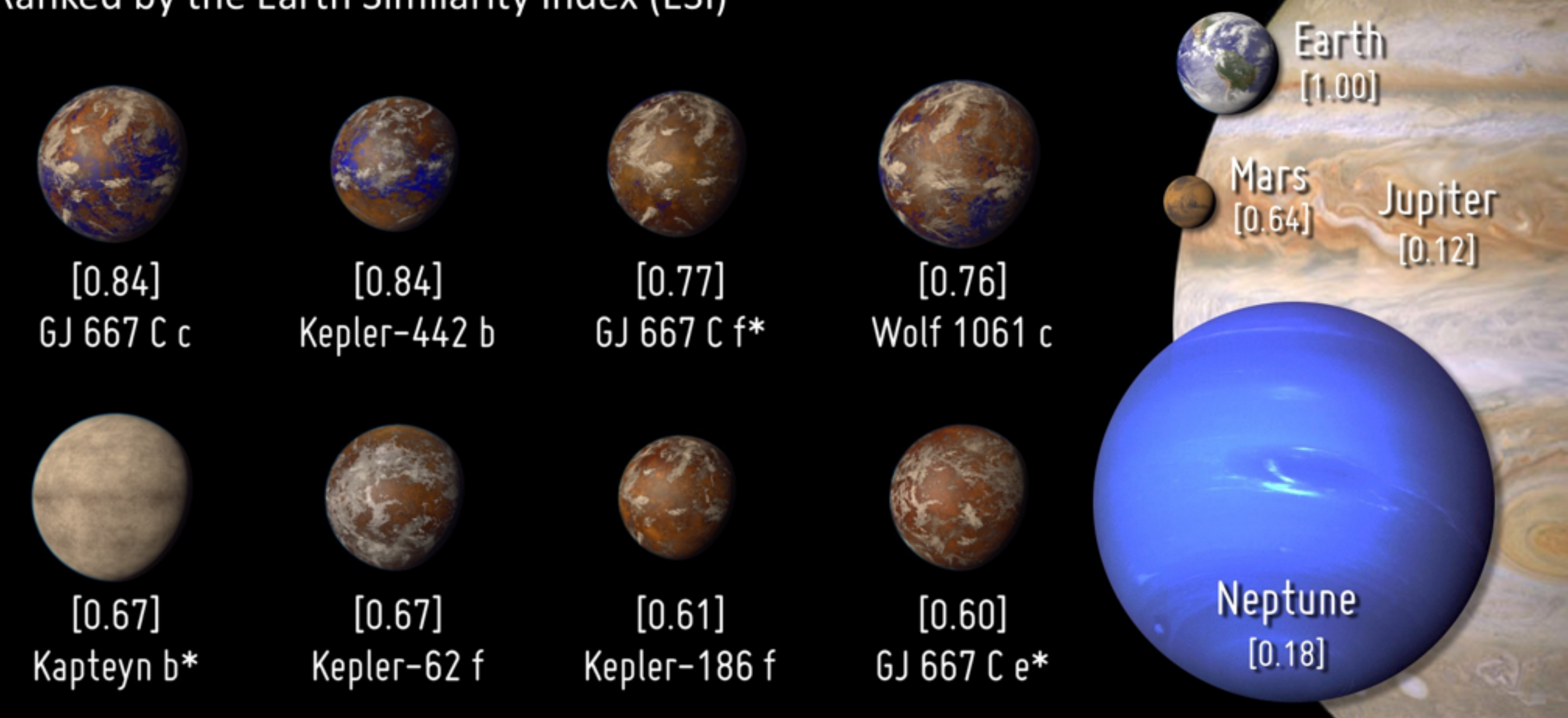
"Advances in Exoplanet Science from Kepler"
Lissauer, Dawson & Tremaine, *Nature* 2014



phl.upr.edu, Jan 2016

Potentially Habitable Exoplanets

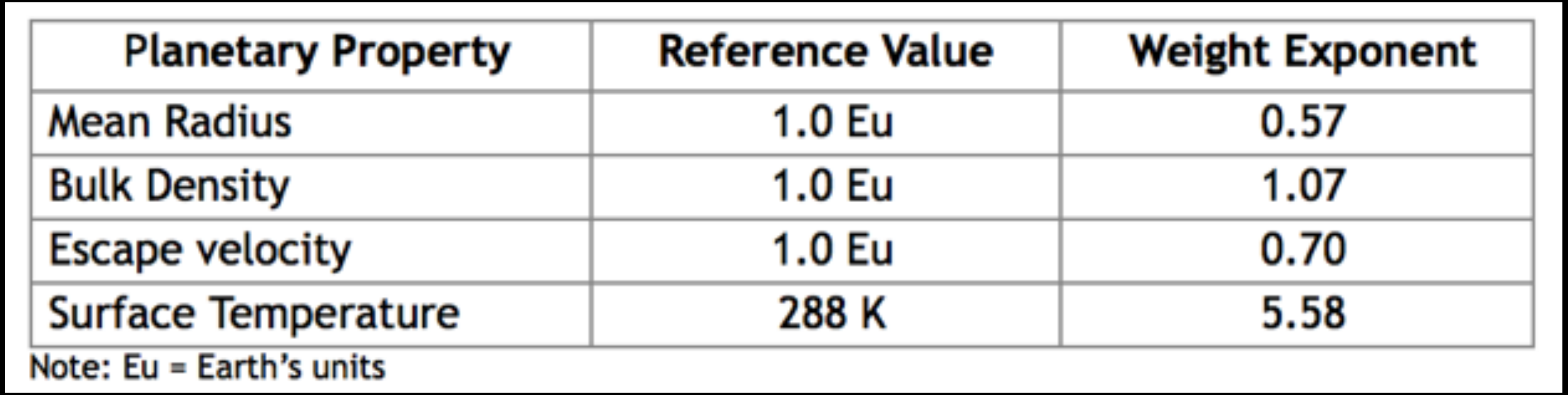
Ranked by the Earth Similarity Index (ESI)



Artistic representations. Earth, Mars, Jupiter, and Neptune for scale. ESI value is between brackets. Planet candidates indicated with asterisks.

CREDIT: PHL @ UPR Arecibo (phl.upr.edu) March 28, 2016

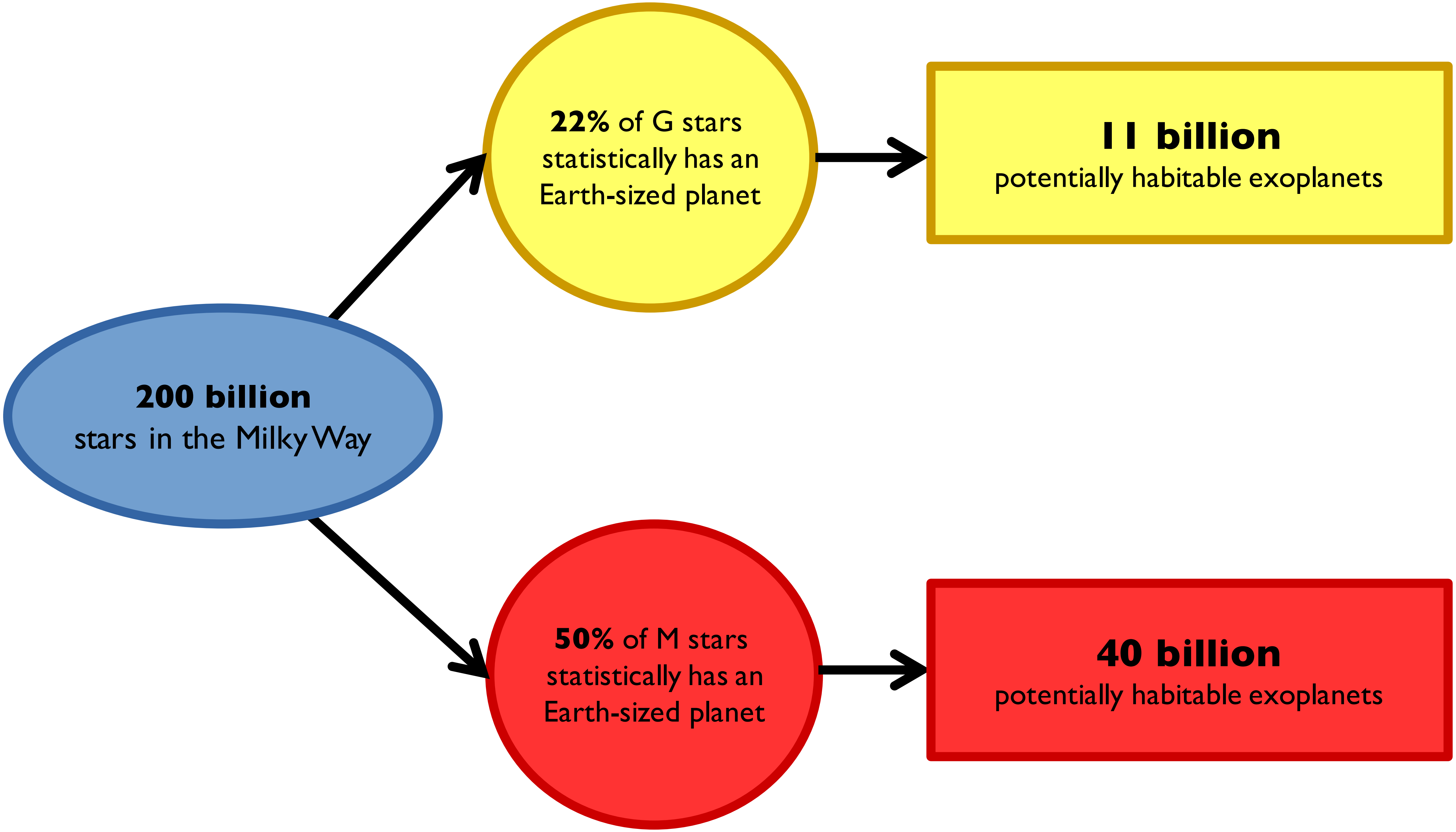
$$\mathrm{ESI} = \prod_{i=1}^{n} \left(1 - \left|\frac{x_i - x_{io}}{x_i + x_{io}}\right|\right)^{\frac{w_i}{n}}$$



Planetary Property	Reference Value	Weight Exponent
Mean Radius	1.0 Eu	0.57
Bulk Density	1.0 Eu	1.07
Escape velocity	1.0 Eu	0.70
Surface Temperature	288 K	5.58

Note: Eu = Earth's units

estimates for the Milky Way



200 billion
stars in the Milky Way

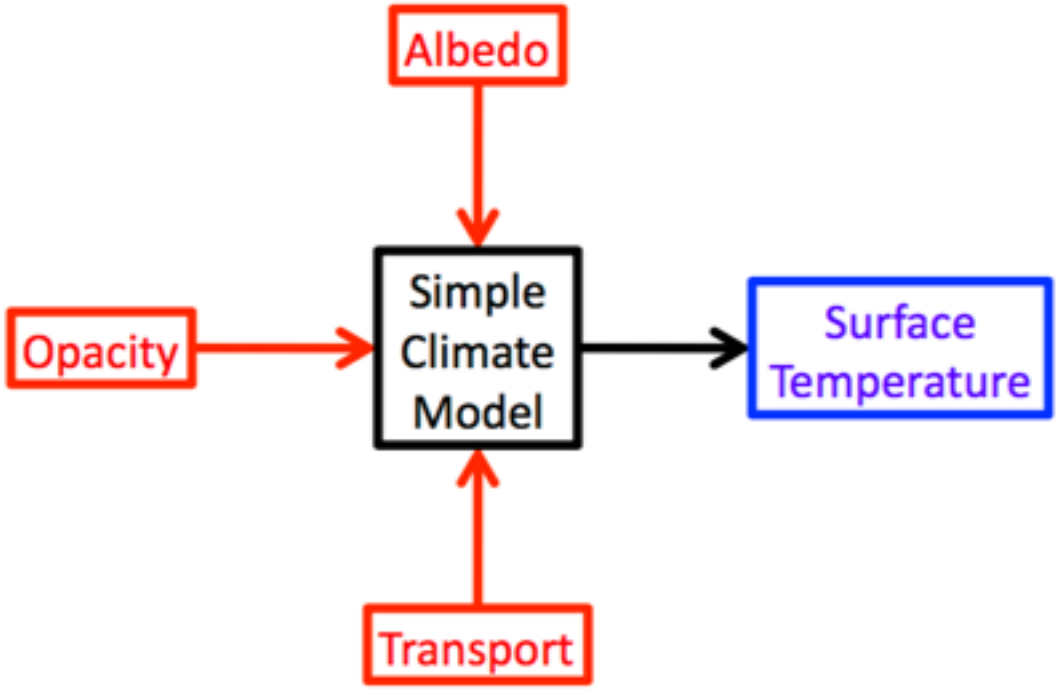
22% of G stars
statistically has an
Earth-sized planet

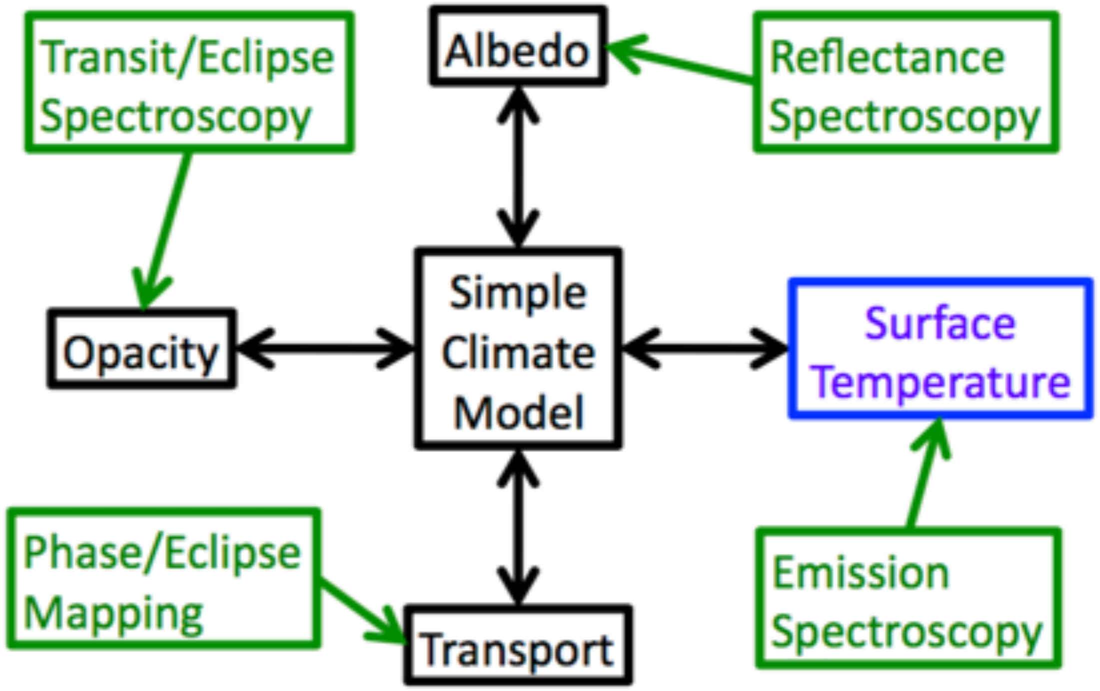
11 billion
potentially habitable exoplanets

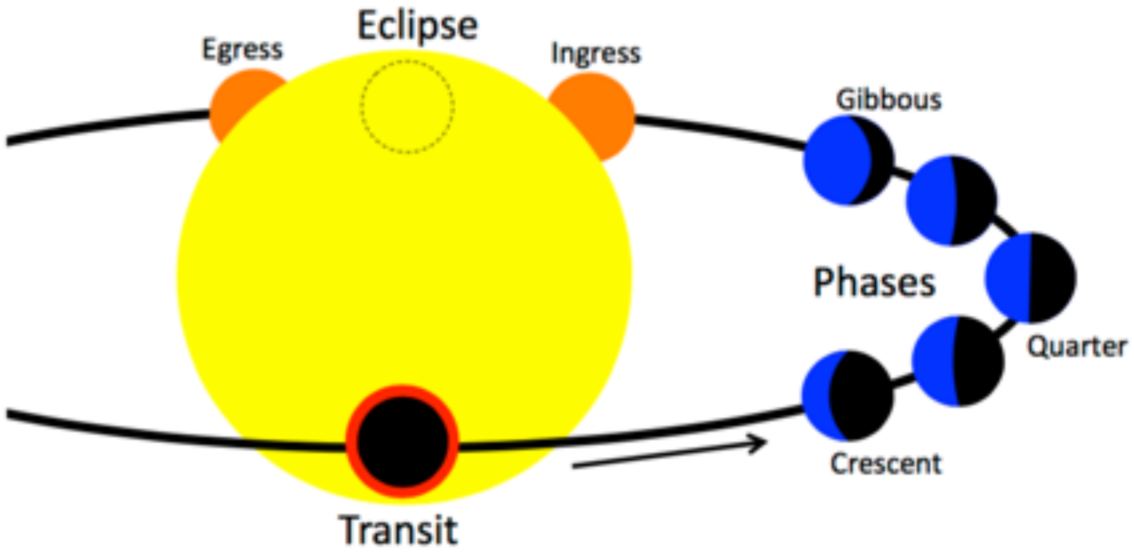
50% of M stars
statistically has an
Earth-sized planet

40 billion
potentially habitable exoplanets

Petigura et al 2013; Kopparapu 2013; Dressing & Charbonneau 2015







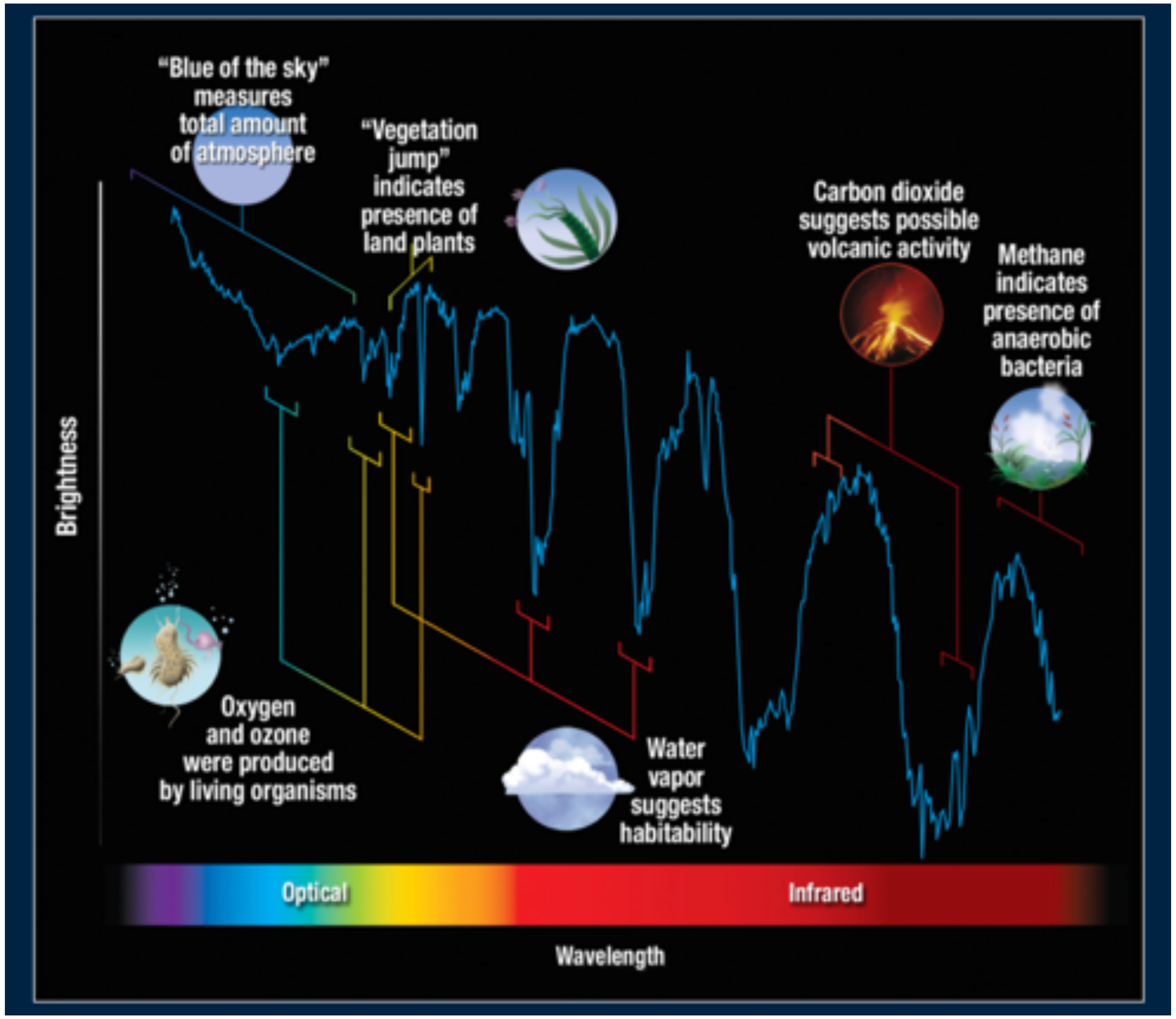
Cowan et al. 2015

in principle, the main factors influencing the climate of exoplanets can be empirically determined by photometric and spectroscopic observations

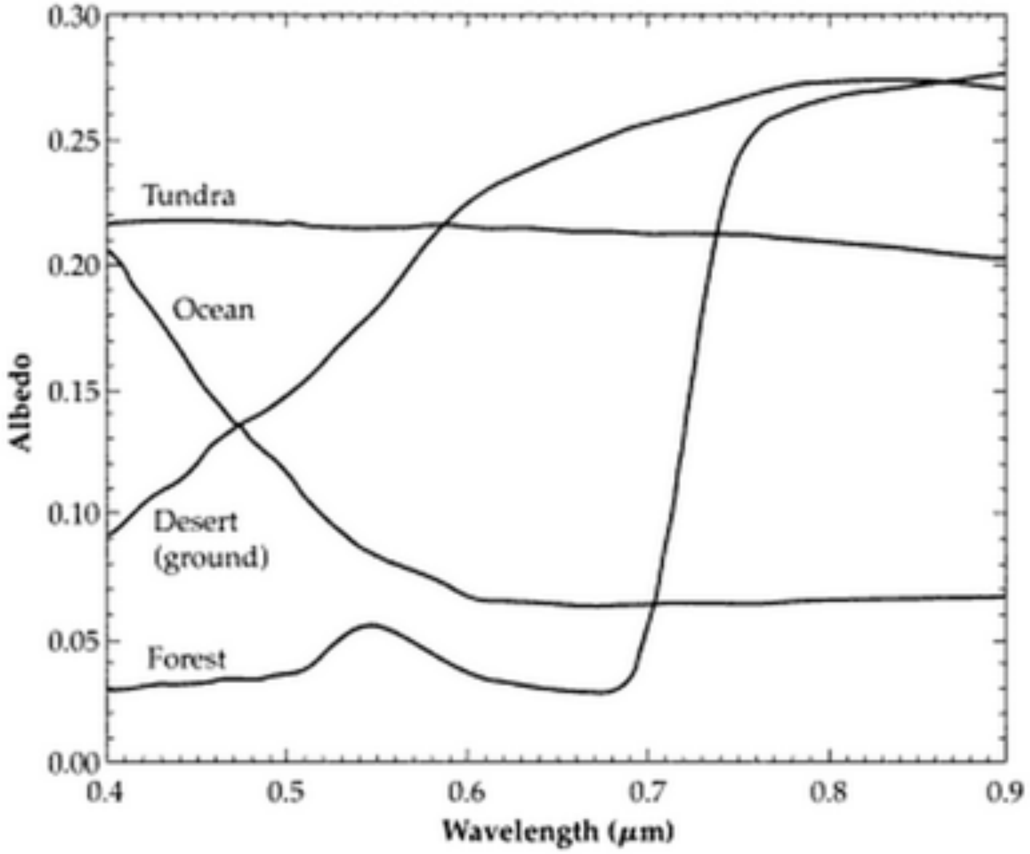
for terrestrial planets this will be extremely difficult, but might be within the reach of next-decade instruments (JWST, E-ELT)

how to look for life (biosignatures)

atmospheric spectrum



surface spectrum



- look for atmosphere with gases out of thermochemical redox equilibrium (ideally, redox pairs such as O_2—CH_4)
- caveats:
  - biosignatures can change significantly over time (cfr. past Earth history)
  - false positives are possible (e.g. O_2 from photodissociation of H_2O)

earth as an exoplanet

before leaving for the Jupiter system, the Galileo probe was used to look for biosignatures from Earth

A search for life on Earth from the Galileo spacecraft

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† Atmospheric and Cometary Sciences Section, Jet Propulsion Laboratory, Pasadena, California 91109, USA
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In its December 1990 fly-by of Earth, the Galileo spacecraft found evidence of abundant gaseous oxygen, a widely distributed surface pigment with a sharp absorption edge in the red part of the visible spectrum, and atmospheric methane in extreme thermodynamic disequilibrium; together, these are strongly suggestive of life on Earth. Moreover, the presence of narrow-band, pulsed, amplitude-modulated radio transmission seems uniquely attributable to intelligence. These observations constitute a control experiment for the search for extraterrestrial life by modern interplanetary spacecraft.

AT ranges varying from ~100 km to ~100,000 km, spacecraft have now flown by more than 60 planets, satellites, comets and asteroids. They have been equipped variously with imaging systems, photometric and spectrometric instruments extending from ultraviolet to kilometre wavelengths, magnetometers and charged-particle detectors. In none of these encounters has compelling, or even strongly suggestive, evidence for extraterrestrial life been found. For the Moon, Venus and Mars, orbiter and lander observations confirm the conclusion from fly-by spacecraft. Still, extraterrestrial life, if it exists, might be quite unlike the forms of life with which we are familiar, or present only marginally. The most elementary test of these techniques—the detection of life on Earth by such an instrumented fly-by spacecraft—had, until recently, never been attempted.

Galileo is a single-launch Jupiter orbiter and entry probe currently in interplanetary space and scheduled to arrive in the Jupiter system in December 1995. It could not be sent directly to Jupiter; instead, the mission incorporated two close gravitational assists at the Earth and one at Venus. This greatly lengthened the transit time, but it also permitted close observations of the Earth. The

NATURE · VOL 365 · 21 OCTOBER 1993

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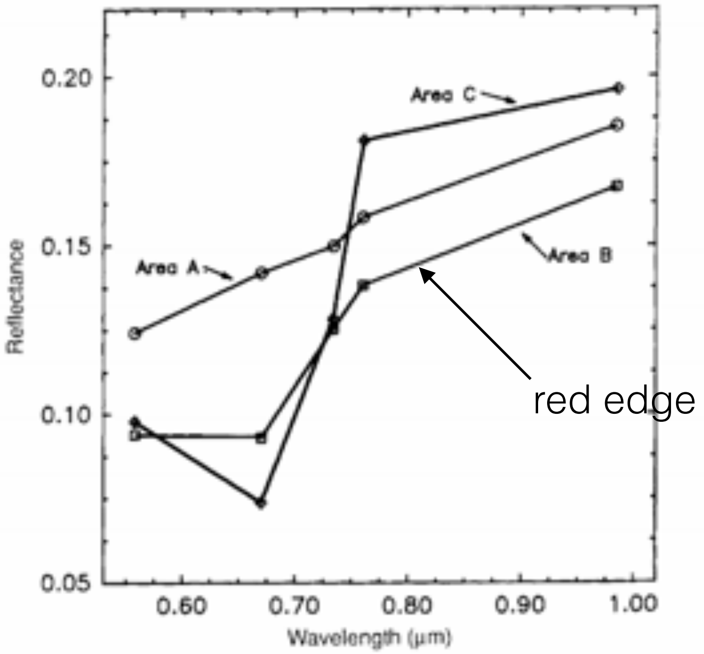


FIG. 3 Representative spectra from three areas on the land surface (see Fig. 2c). A gently sloping spectrum (circles, Area A) is consistent with any of several types of rock or soil. An intermediate spectrum (squares, Area B) shows some evidence of an absorption band near 0.67 μm (RED). Substantial areas on the surface have an unusual spectrum (diamonds, Area C) with a strong absorption in the RED band and a steep band edge just beyond 0.7 μm. This spectrum is inconsistent with all likely rock and soil types, and is plausibly associated with photosynthetic pigments (see text).

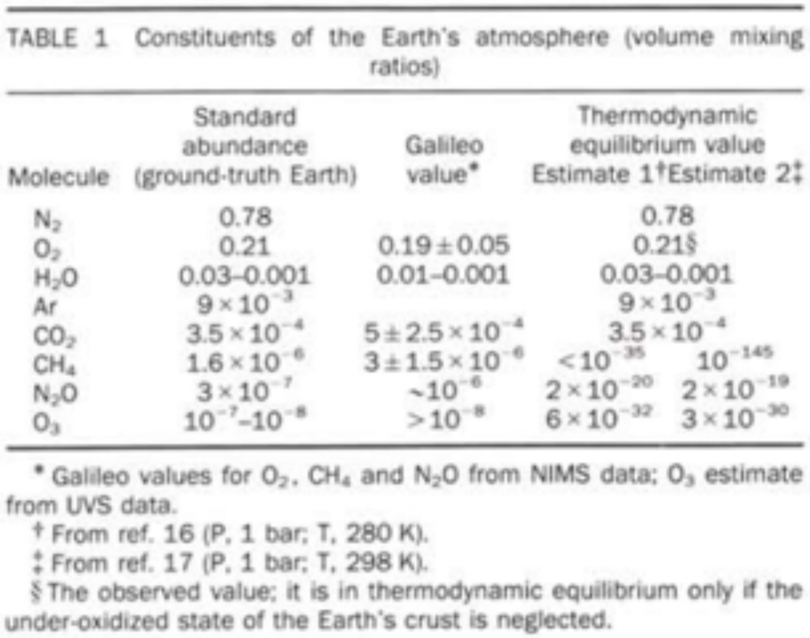
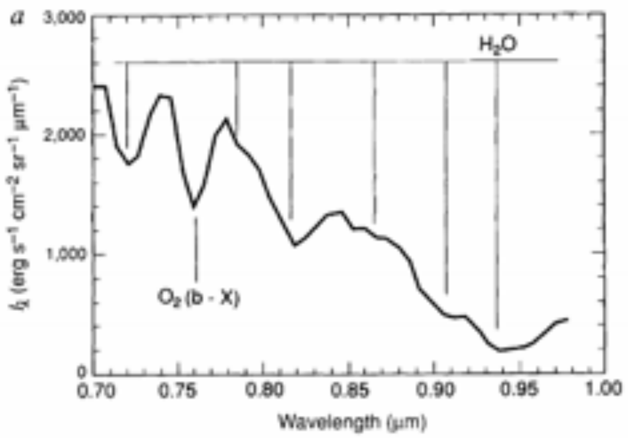


TABLE 1 Constituents of the Earth's atmosphere (volume mixing ratios)

Molecule	Standard abundance (ground-truth Earth)	Galileo value*	Thermodynamic equilibrium value Estimate 1†	Estimate 2‡
N_2	0.78		0.78	
O_2	0.21	0.19 ± 0.05	0.21§	
H_2O	0.03–0.001	0.01–0.001	0.03–0.001	
Ar	9×10^{-3}		9×10^{-3}	
CO_2	3.5×10^{-4}	$5 \pm 2.5 \times 10^{-4}$	3.5×10^{-4}	
CH_4	1.6×10^{-6}	$3 \pm 1.5 \times 10^{-6}$	$< 10^{-35}$	10^{-145}
N_2O	3×10^{-7}	$\sim 10^{-6}$	2×10^{-20}	2×10^{-19}
O_3	10^{-7}–10^{-8}	$> 10^{-8}$	6×10^{-32}	3×10^{-30}

* Galileo values for O_2, CH_4 and N_2O from NIMS data; O_3 estimate from UVS data.
† From ref. 16 (P, 1 bar; T, 280 K).
‡ From ref. 17 (P, 1 bar; T, 298 K).
§ The observed value; it is in thermodynamic equilibrium only if the under-oxidized state of the Earth's crust is neglected.



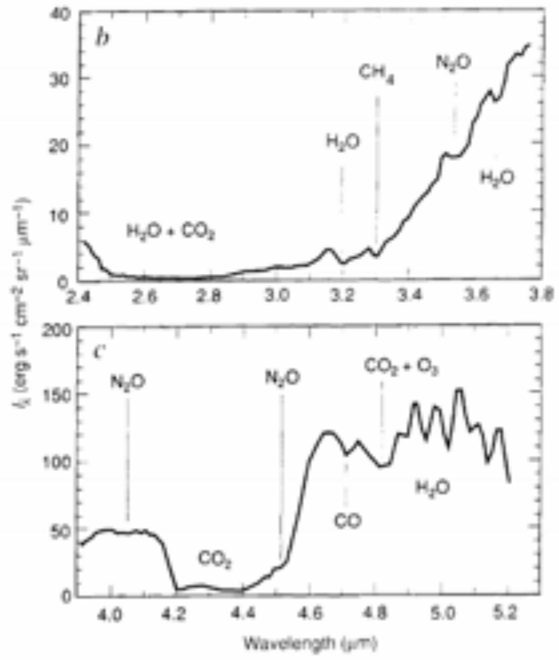
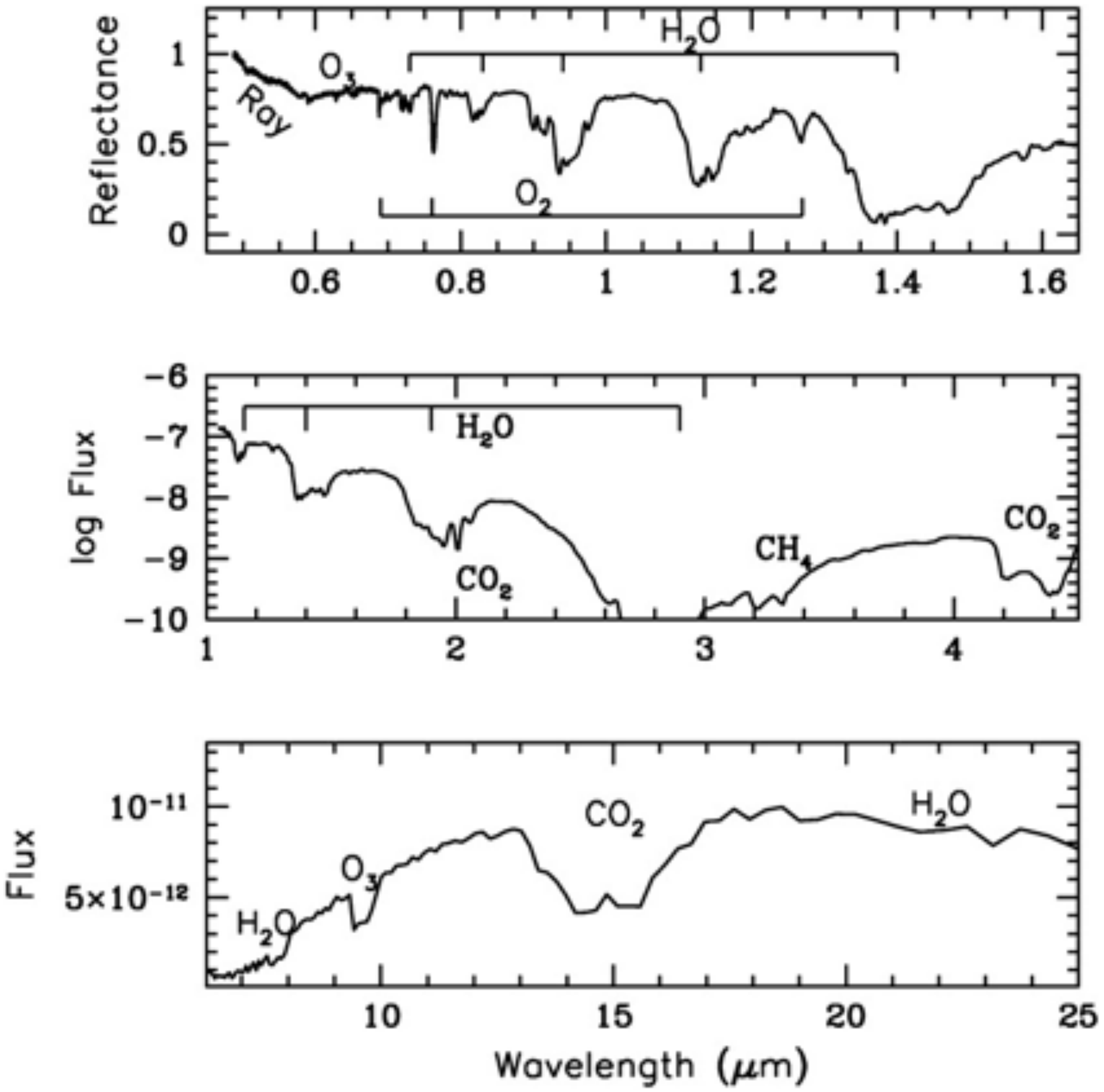


FIG. 1 a, Galileo long-wavelength-visible and near-infrared spectra of the Earth over a relatively cloud-free region of the Pacific Ocean, north of Borneo. The incidence and emission angles are 77° and 57° respectively. The ($b^1\Sigma_g^+$—$X^3\Sigma_g^-$) 0–0 band of O_2 at 0.76 μm is evident, along with a number of H_2O features. Using several cloud-free regions of varying airmass, we estimate an O_2 vertical column density of 1.5 km-amagat ± 25%. b and c, Infrared spectra of the Earth in the 2.4–5.2 μm region. The strong υ_3 CO_2 band is seen at the 4.3 μm, and water vapour bands are found, but not indicated, in the 3.0 μm region. The υ_3 band of nitrous oxide, N_2O, is apparent at the edge of the CO_2 band near 4.5 μm, and N_2O combination bands are also seen near 4.0 μm. The methane (0010) vibrational transition is evident at 3.31 μm. A crude estimate[10] of the CH_4 and N_2O column abundances is, for both species, of the order of 1 cm-amagate (≡1 cm path at STP).



(*Top*) Visible wavelength spectrum from Earthshine measurements plotted as normalized reflectance (Turnbull et al 20067).

(*Middle*) Near-IR spectrum from NASA's Extrasolar Planet Observation and Deep Impact Extended Investigation mission, with flux in units of watts meter^{-2} micrometer^{-1} (Robinson et al. 2011).

(*Bottom*) Mid-IR spectrum as observed by Mars Global Surveyor en route to Mars, with flux in units of Watts meter^{-2} Hertz^{-1} (Christensen et al 1997)

Seager 2014

- obtaining similar atmospheric spectra for Earth-like planets is not a near-term goal
- some nearby super-Earth atmospheres around M-dwarfs might be observable in a ten-year time span (e.g. from JWST or ground based large telescopes)
- lots of theoretical modeling + laboratory measurements needed in the meantime ("Atmosphere in a Test-Tube" project, with R. Claudi et al.)

extremophiles survival (and biosignatures) in simulated icy moons environments

with D. Billi (U. Tor Vergata), A. Ceccarelli, E. Pettinelli (U. Roma Tre)

Sample preparation to study extremophile survival in laboratory ice-liquid water systems simulating salt (or acid)/ice mixtures, as expected for the icy crusts of Europa, Ganymede, Callisto and Enceladus.

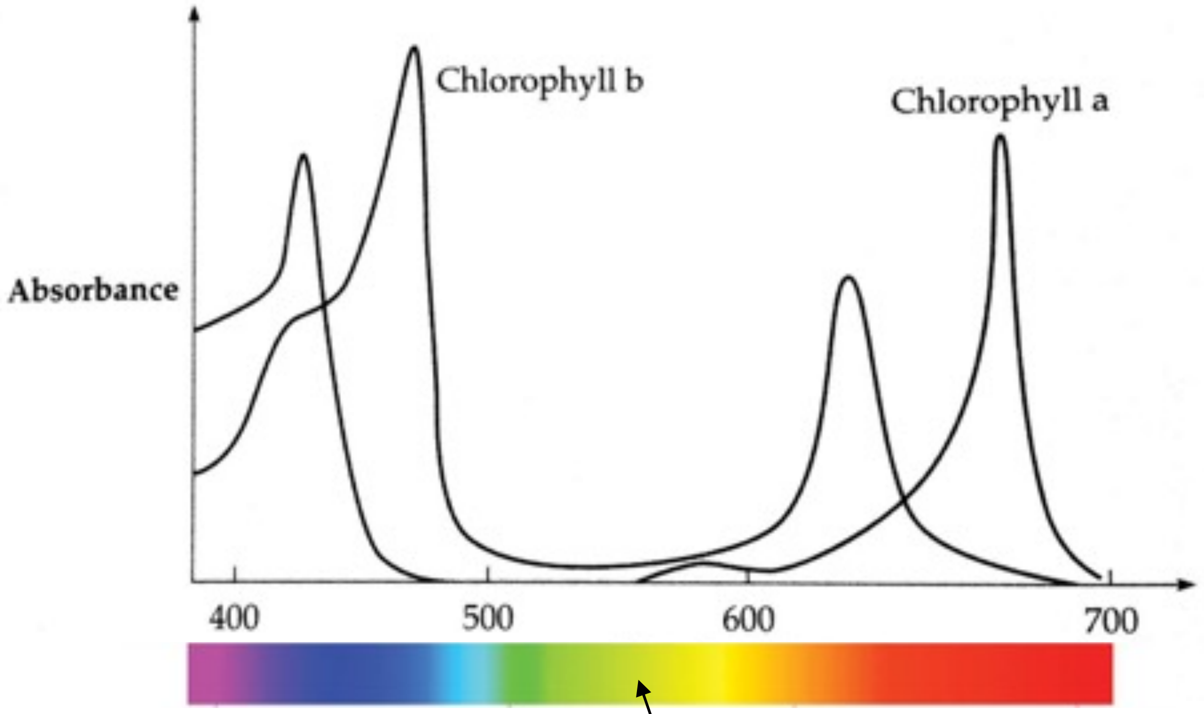
The project uses the cold camera facility in Roma Tre and the collection of extremophiles in Roma Tor Vergata.

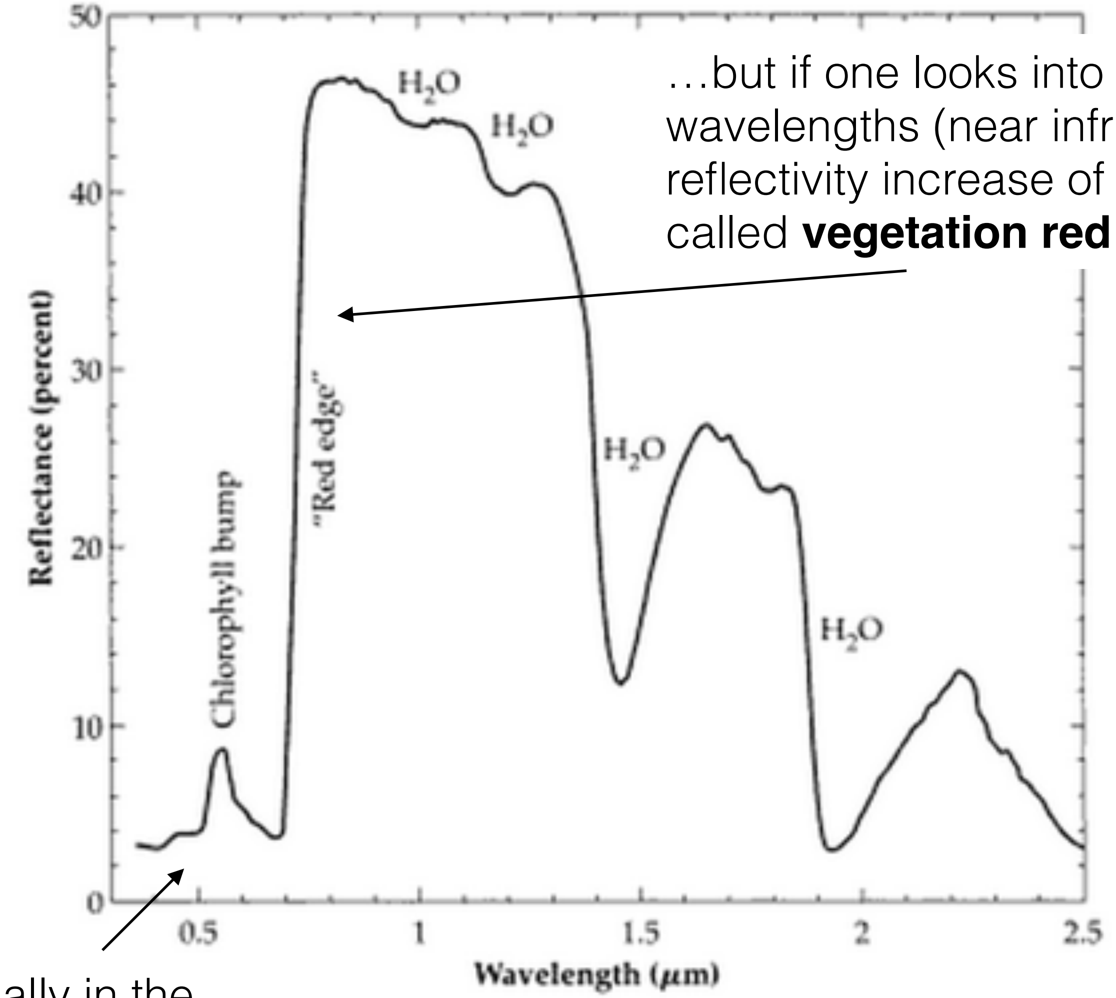
In addition to studying the survival rates, we plan to conduct spectroscopic measurements on the ice samples in order to detect differences due to the presence of living organisms.

photosynthesis around M-dwarfs

with R. Ferrazzoli, D. Billi (U. Tor Vergata)

chlorophyll absorbs light preferentially at wavelengths ~450 nm and ~680 nm…





…but if one looks into even longer wavelengths (near infrared) finds a reflectivity increase of a factor 10 called **vegetation red edge**

… and is reflected preferentially in the green part of the spectrum

the red edge might be a useful biosignature, but there can be abiotic mechanisms producing similar lines; also, photosynthetic life around other stars with different emission spectra can have adapted differently super-Earth around M dwarfs stars are an interesting target:

- M dwarfs are more abundant and long-lived than G-type stars
- transits are easier to detect with present-day technology (shorter period, larger flux variation during transit)
- lower levels of UV radiation in older M stars, decreasing the probability of destruction of biosignature gases and of false positives

but: habitable zone is closer to the star (tidal locking, flares, etc)

theoretical studies of the possibility of “exo-vegetation” (Wolfencroft & Raven 2002, Kiang et al 2007) + the existence of alternative photosynthetic paths on Earth (Mielke et al., 2011; Gan and Bryant, 2015), motivate the study of photosynthesis around M dwarfs

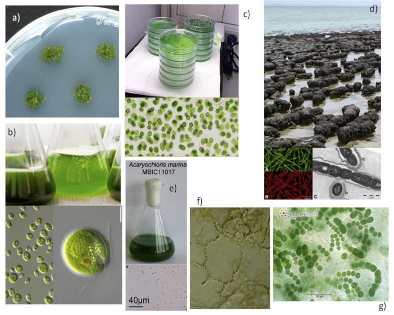
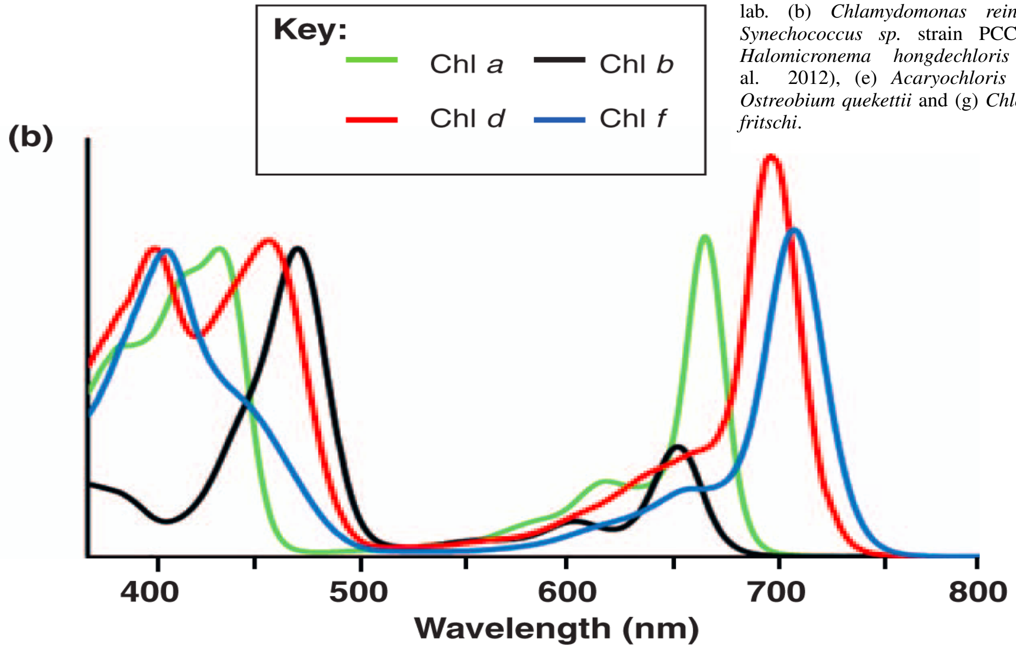


Fig. 1. In figure we can see samples of (a) *Physcomitrella* growing on agar plates by Sabisteb−Anja Martin from the Ralf_Reski lab. (b) *Chlamydomonas reinhardtii*, (c) *Synechococcus sp.* strain PCC 7002, (d) *Halomicronema hongdechloris* (Chen et al. 2012), (e) *Acaryochloris marina*, (f) *Ostreobium quekettii* and (g) *Chlorogloeopsis fritschi*.

1. study the response of extremophile microorganisms capable of photosynthesis in the IR to simulated M starlight
2. measure the reflectance spectra of such organisms in laboratory conditions
3. model the expected signal from realistic exoplanetary surface coverage

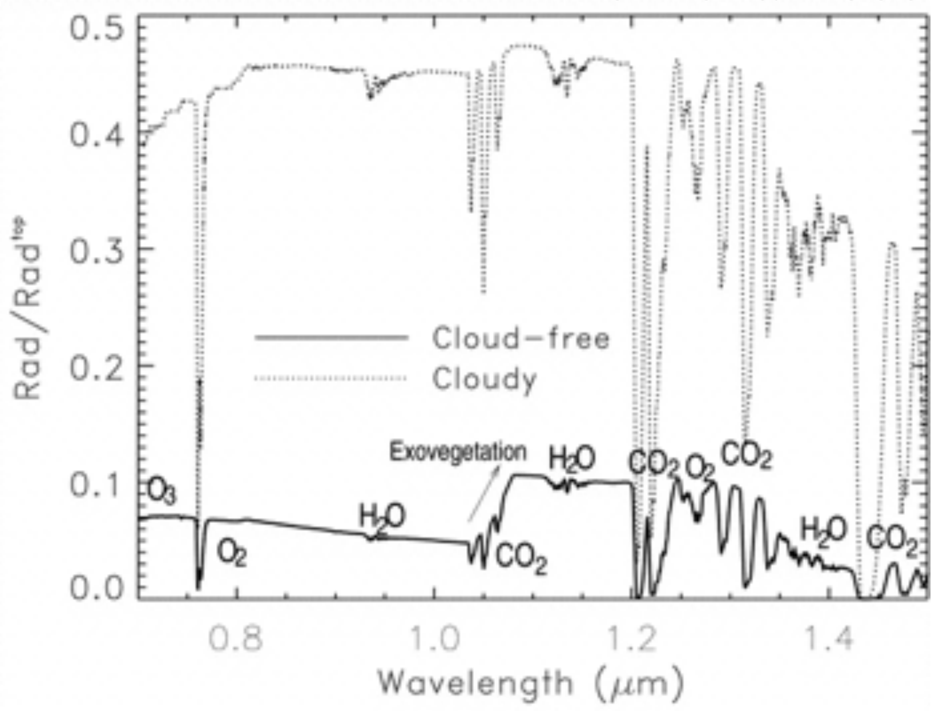


TRENDS in Plant Science

real observations will be extremely challenging

- the planet is unresolved, and its light is not separable from that of the star
- cloud coverage introduces significant uncertainty

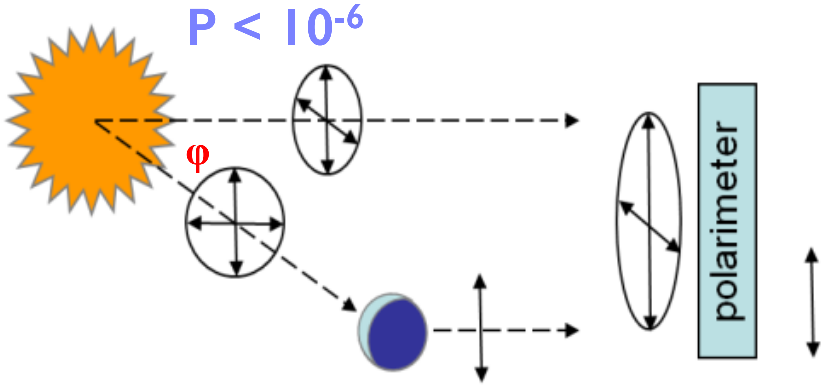
Tinetti et al 2006



observing the polarized signal might increase the chance of detecting and distinguishing photosynthetic pigments (use phase modulation, angle dependence, differential measurement)

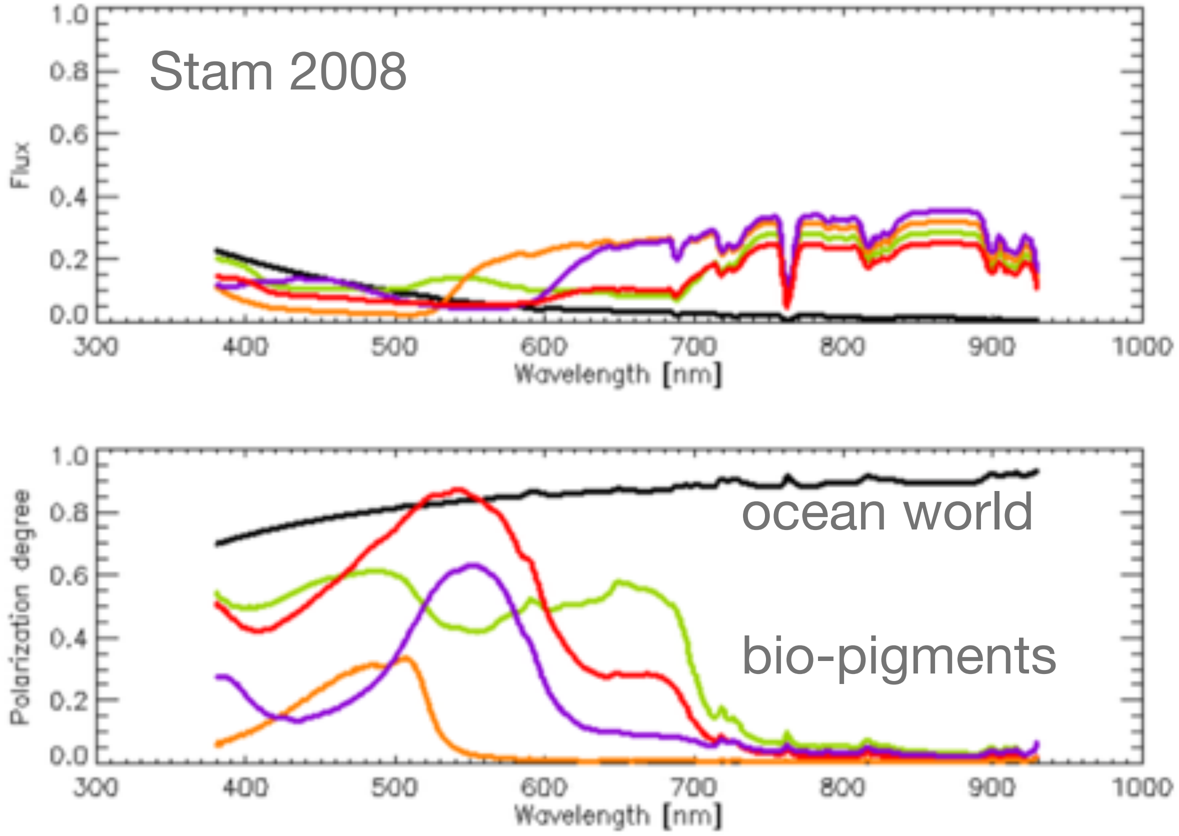
Stellar light, unpolarized:

$P < 10^{-6}$



Light scattered by atmosphere/surface,
linearly polarized perpendicular to scattering plane

$P = 10^{-2} - 1$


Stam 2008

ocean world

bio-pigments

Conclusions

- astrobiology is a relatively new field, and requires a very broad range of competences from different research areas: interdisciplinary collaboration is strongly encouraged
- in the coming years, new data will allow for the possibility of searching for signs of life beyond Earth, both in and out the solar system
- in the near term, a number of existing and planned astrophysical observations have a relevance for the topic:
  - exoplanets discovery and characterization from space:
    - CHEOPS (ESA, 2017)
    - PLATO (ESA, 2024)
    - TESS (NASA, 2017)
    - JWST (NASA, 2018)
    - ARIEL (ESA, proposed, 2026)
  - exoplanets discovery and characterization from the ground:
    - HARPS (@3.6 m La Silla Observatory Chile, operative)
    - HARPS-N (@3.6 m Telescopio Nazionale Galileo, La Palma, operative)
    - ESPRESSO (@8 m Very Large Telescope, Chile, 2016)
    - CODEX (@39 m Extremely Large Telescope, Chile, 2024)
  - solar system exploration
    - JUICE (observation of Jupiter icy moons, launch planned in 2028),
    - ExoMars (first phase in action, second phase launches in 2018)
- very long term goal: direct imaging of earth-like exoplanets
- lots of theoretical work & modeling need (habitability, biosignatures, etc)
- very exciting prospects, but chances of success depends on how common life is: anyway, we will learn much along the way…